TP 8487E

Towed Resistance Trials In Ice Of The USCGC Mobile Bay (WTGB 103)

Volume 1: Final Report
September 1986

Transport Canada
Development

Transports Canada
Developpement

U.S. COAST GUARD
ENGINEERING

U.S. DEPARTMENT OF TRANSPORTATION
MARITIME ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT

103
COAST GUARD

CA1
DTC 800
86
T56
v.1
c.2

89-00606/

CA1
DTC800
86
T56
V.1
c.2

ARCTEC CANADA LIMITED

FR 1923E
TP 8467E

TOWED RESISTANCE TRIALS IN ICE OF THE USCGC MOBILE BAY (WTGB103)

VOLUME 1 - FINAL REPORT

Library and Information Centre / Centre de Documentation (GSLA)
RECEIVED - REÇU LE
APR 26 1988
Transport Canada / Transports Canada

By:

L. PHILLIPS
P. ZAHN

SEPTEMBER 1986

SUBMITTED TO:

Transportation Development Centre,
Guy Favreau Complex,
200 Dorchester Blvd. West,
Suite 601, West Tower,
Montreal, Quebec.
H2Z 1X4

SUBMITTED BY:

ARCTEC CANADA LIMITED
311 Legget Drive,
Kanata, Ontario.
K2K 1Z8

372595

PROJECT TEAM CONSISTED OF:

ARCTEC CANADA LIMITED	and	ARCTEC ENGINEERING INC.
I. F. GLEN L. D. PHILLIPS D. FRERE		J.L. COBURN P. ZAHN

with technical assistance from:

T. JOHNSTONE
A. LEMIEUX

and others.

THE CONTENTS OF THIS REPORT REFLECT THE VIEWS OF THE CONTRACTOR AND NOT NECESSARILY THE OFFICIAL VIEWS OF THE TRANSPORTATION DEVELOPMENT CENTRE.

Un sommaire en français de ce document est inclus avant la tables des matières.

APPROVED BY ______________________

IAN F. GLEN, PRESIDENT.

Transport Canada Transports Canada
Development Développement

REPORT DOCUMENTATION FORM

1. Transport Canada Report No.
TP 8487E

2. TDC Project No.
6481/6482/6483

3. Recipient's Catalogue No.

4. Title and Subtitle
Towed Resistance Trials in Ice of the USCGC Mobile Bay (WTGB103)

5. Report Date
September 1986

6. Performing Organization Report No.
1923E

7. Author(s)
L.D. Phillips, P.Z. Zahn

8. Transport Canada File No.
D1460-181-3

9. Performing Organization Name and Address
Arctec Canada Limited
311 Legget Drive
Kanata, Ontario
K2K 1Z8

10. DSS File No.
11SD.T8200-5-5531

11. DSS or Transport Canada Contract No.
0SD85-00142

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
200 Dorchester Blvd. West
Suite 601, West Tower
Montreal, Quebec H2Z 1X4

13. Type of Report and Period Covered
Final

14. Sponsoring Agency Code

15. Supplementary Notes
Volume 1 - Final Report
Volume 2 - Appendices

16. TDC Project Officer
I.M. Bayly

17. Abstract

This report presents the methodology and results of a joint Canadian and American program of full scale towed resistance trials, and represents a major milestone in the ability to predict the operational performance of ships in ice. An extensive series of towed resistance tests and corresponding self-propulsion tests involving the USCGC MOBILE BAY were carried out under the auspices of the Arctic Ship Trafficability Program. The trials have provided the first full scale verification of icebreaker resistance. Testing was carried out in Lake Michigan at various speeds and in a range of thicknesses of level, unbroken ice. Thrust, torque, propeller RPM, speed and towing pull were recorded. The results have been compared to established ice resistance formulations to assess the influence of different test parameters. An improved empirical resistance prediction equation has been derived. Trends in thrust deduction, wake fraction and propulsive efficiency components have been examined and compared to model test results for the 140' WTGB class hull form. The correlation between full scale test data and model scale predictions has been assessed. Recommendations are presented which affect design procedures and ice basin test methods for assessing propulsive performance of icebreaking ships.

18. Key Words
Full scale trials, resistance, performance prediction, icebreakers

19. Distribution Statement
Limited number of copies are available from the Transportation Development Centre.

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price
Unclassified	Unclassified	184	Nil

TDC/CDT 79-005
Rev 86

Canada

Transports Canada Transport Canada
Développement Development

FORMULE DOCUMENTAIRE DU RAPPORT

1. Nº du rapport Transports Canada TP 8487E	2. Nº de l'étude — CDT 6481/6482/6483	3. Nº de catalogue du destinataire
4. Titre et sous-titre Towed Resistance Trials in Ice of the USCGC Mobile Bay (WTGB103)		5. Date du rapport Septembre 1986 6. Nº du rapport de l'organisme exécutant 1923E
7. Auteur(s) L.D. Phillips, P.Z. Zahn		8. Nº de dossier Transports Canada D 1460-181-3
9. Nom et adresse de l'organisme exécutant Arctec Canada Limited 311 Legget Drive Kanata, Ontario K2K 1Z8		10. Nº de dossier — ASC 11SD.T8200-5-5531 11. Nº de contrat — ASC ou Transports Canada 0SD85-00142
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 200 ouest, boul. Dorchester Suite 601, tour ouest Montréal (Québec) H2Z 1X4		13. Genre de rapport et période visée Final 14. Code de l'organisme parrain
15. Remarques additionnelles Volume 1 - Rapport final Volume 2 - Annexes		16. Agent de projet — CDT I.M. Bayly

17. Résumé

Ce rapport présente le mode opératoire et les résultats des essais de résistance à l'avancement d'un navire réel remorqué, le USCCG MOBILE BAY. Faits dans le cadre d'un programme conjoint canado-américain, désigné Arctic Ship Trafficability Program, ces essais constituent un jalon important dans l'évolution des techniques de prévision des performances réelles des navires dans les glaces. Ils ont été réalisés, aussi bien les essais de traction que les essais d'autopropulsion correspondants, dans le lac Michigan à diverses vitesses et dans diverses épaisseurs de glace uniforme et intacte. C'était la première fois que l'on vérifiait en vraie grandeur la résistance à la marche d'un brise-glace. Les paramètres mesurés ont été la poussée, le couple, le régime de rotation de l'hélice, la vitesse et l'effort de traction. Par la suite, les résultats ont été comparés aux valeurs théoriques dérivées d'équations établies de résistance des glaces en vue d'évaluer l'influence des différents paramètres d'essai. Cet exercice a débouché sur une équation empirique de résistance des glaces à l'avancement qui serre la réalité de plus près. Les chercheurs ont suivi l'évolution des coefficients de succion et de sillage ainsi que du rendement propulsif global, et ils les ont comparés aux résultats d'essais sur modèle réduit d'une coque d'une classe WTGB de 140 pieds de longueur. Ils ont également recherché la corrélation existant entre les résultats des essais en vraie grandeur et les prévisions tirées des essais en bassin. Le rapport se termine par des recommandations qui influenceront les techniques de conception des brise-glace et les méthodes de détermination de leur rendement propulsif à partir d'essais en bassin des glaces.

18. Mots-clés Essai en vraie grandeur, résistance à la marche, prévision des performances, Brise-glace.	19. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

20. Classification de sécurité (de ce rapport) non classifié	21. Classification de sécurité (de cette page) non classifiée	22. Nombre de pages 184	23. Prix Aucun

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Fred Seibold of the Maritime Administration, CDR Dave Humphreys of the U.S. Coast Guard; and Mr. Ian Bayly of Transport Canada for their interest and support of this venture. The coordination and impetus provided by Captain Joseph Wubbold and the staff of the U.S. Coast Guard Ice Operations office was also critical to the overall success of the program.

The advice, cooperation and superior professional capabilities of the officers and crew of both MACKINAW and MOBILE BAY must be credited with carrying the tests far beyond the expected operational goals. They displayed a remarkable ability to perform unprecedented operations and provide effective solutions to operational problems. In particular, the efforts of LT John DeJung, Commanding Officer - MOBILE BAY; and Capt. Arnold Litteken, Commanding Officer - MACKINAW, in all areas of planning, liaison, and seamanship were unsurpassed in our experience.

SUMMARY

This report presents the results of full scale towed resistance and self-propelled trials of the U.S. COAST GUARD icebreaking tug MOBILE BAY. The trials were carried out in level ice in the northern Green Bay region of Lake Michigan to establish a full scale reference line for use in predicting performance of ships in ice. The program was jointly sponsored by the United States Coast Guard, U.S. Maritime Administration and Transport Canada (Transportation Development Centre). The primary objectives of the trials program were to obtain reliable full scale measurements of:

- Towed resistance of MOBILE BAY in uniform level ice;
- Self-propelled performance of MOBILE BAY in level ice; and
- Ice thickness and flexural strength to support the trials results.

The MOBILE BAY belongs to the Bay class of Great Lakes icebreaking tugboats which are collectively designated "140 foot WTGB", in reference to their design waterline length and hull form type. The USCGC MACKINAW participated in these exercises as the towing vessel and as a base of operations.

A sophisticated instrumentation system was installed on MOBILE BAY to record data and to monitor the towing operations. A large region of suitable level ice was located and testing commenced in February 1986. The weather during the trials program was fair and no delays occurred. A larger than expected range of ice thickness was encountered which enhanced the value of the data set. Thrust, torque, propeller RPM, speed and towline tension were recorded. The data collected during these trials were consistent and of high quality. A summary of the data set is given in Table 1.

Total Resistance

The most significant results of this study are the tabulated full scale measurements of hull resistance for the MOBILE BAY, which correspond to a range of ship velocities and ice thickness. This full scale resistance data is unique and provides a basis for a rational revision of performance prediction methods.

Ice Resistance

Pure ice resistance data was obtained from the total resistance by subtracting the open water resistance. Since no full scale open water towing data was available this open water resistance was estimated from model tests. The numerical analysis of the ice resistance data included a comprehensive assessment of dimensionless parameters and empirical relationships used in earlier studies.

TABLE 1

RANGE OF FULL SCALE MEASURED DATA

TOWED RESISTANCE

No. of Points: 17

Velocity Range: 1.1 - 7.6 knots

Thickness Range: 32 cm - 52 cm (40.4 cm average)

Resistance Range: 49,000 N - 169,000 N

SELF-PROPELLED

No. of Points: 31

Velocity Range: 0.4 - 6.8 knots

Thickness Range: 26.7 cm - 48.3 cm

Applied Horsepower Range: 400 - 2500 SHP (300-1900 kv)

ICE STRENGTH

No. of Points: 14

Average Strength: 454 kPa

Range of Strength: 283 - 648 kPa

Average Strain Rate: 7.3×10^{-3} 1/sec

It was found that the empirical equation which provided the best numerical fit to the data had the form:

$$R_i/\rho_w gBh^2 = 4.254 + 3.963 \times 10^{-5} (V/\sqrt{gB})^2 (L/h)^3$$

Figure 1 compares the equation (E), extracted from the towed trials, to several general prediction equations derived from WTGB model data or other sources. The present equation was found to have a correlation of 0.96. However the ice thickness range was limited and there was insufficient variation to determine the influence of flexural strength. Further investigation is required to generalize and improve this equation.

The MOBILE BAY towed resistance data has confirmed earlier results (Tatinclaux 1984) which concluded that predictions from model resistance were significantly in excess of the full scale measurements (Figure 2). A reassessment of data from tests in urea ice and saline ice at CRREL (West 1975) and Arctec (Lecourt 1975) respectively, showed that the saline ice results were in somewhat better agreement with the towed trials data. The urea ice tests predicted higher values.

A number of factors have been identified which may introduce distortions into the results at either full scale or model scale. It was thought that the channel broken by the MACKINAW in preparation for towing the MOBILE BAY could have resulted in a relief of pressure on the MOBILE BAY thereby causing a reduction in resistance. However, an analysis of the self-propelled trials did not show a significant variation in thrust between the free route (in ice) trials and corresponding tests where a broken channel was parallel to the MOBILE BAY track. This suggested that the influence of confinements on the towed resistance was not responsible for any discrepancy between the trials results and model test results. Instead, it is believed that the resistance predicted on the basis of model tests is influenced by variations in hull-ice friction, model ice density and ice failure mechanics (Appendix A).

The observation that model resistance is greater than towed resistance was expected and is common in model tests. This may result from a general practice in ice basin tests, where unrealistic ice strengths and friction values are used and then the results are corrected by an ice strength factor. There was no support for the existence of an ice strength term in the present trials data.

The discrepancy between saline and urea ice results has also led to an hypothesis that the crushing strength may be incorrectly modelled with existing refrigerated model ice materials and that this may be a significant factor in resistance prediction. On the basis of M.V. ARCTIC model tests (Phillips, 1986) and comparisons to full scale trials; a pressure-area scaling relationship has been defined which leads to a much weaker crushing strength.

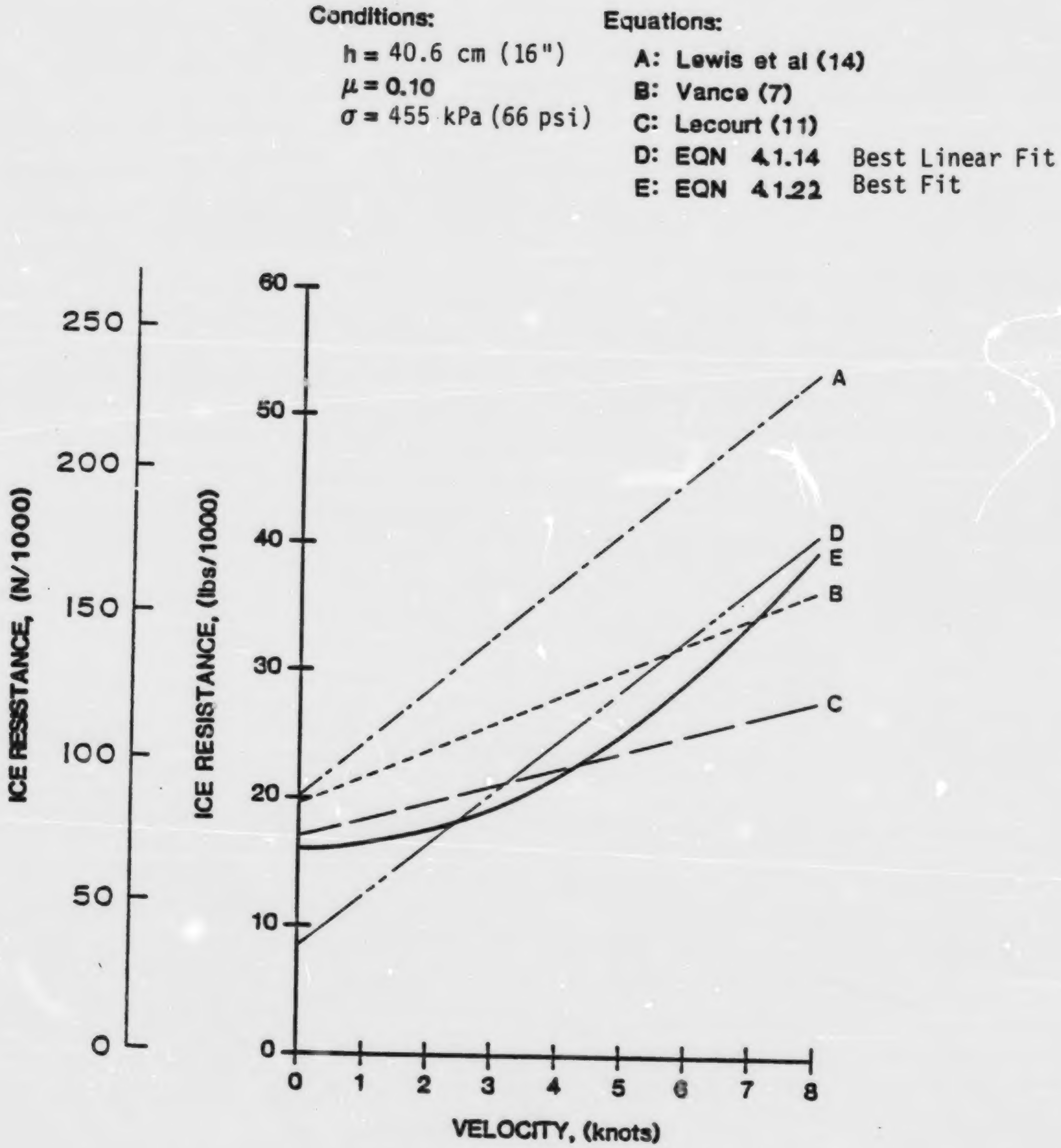


Figure 1

RESISTANCE ESTIMATES USING EMPIRICAL EQUATIONS

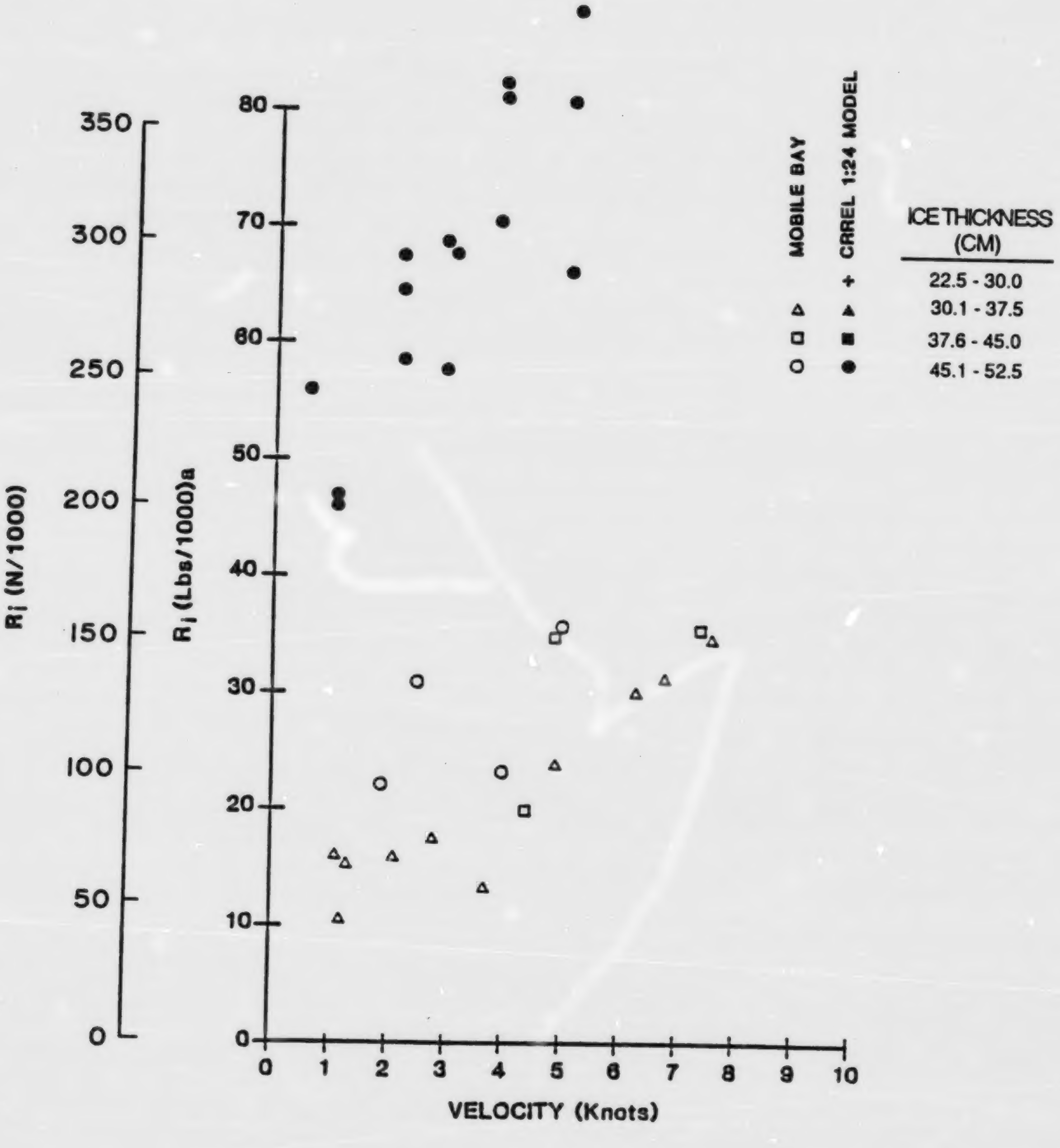


Figure 2
COMPARISON OF MOBILE BAY DATA WITH CRREL 1:24 SCALE MODEL

Self-Propulsion Analysis

In 1979 the KATMAI BAY, a sister ship of the MOBILE BAY, had carried out self-propulsion trials in similar ice conditions as in the current tests. The two data sets were found in excellent agreement for K_T, K_Q and wake fraction. When the MOBILE BAY resistance equation was used as a basis for calculating the KATMAI BAY thrust deduction fraction, it was also found to be virtually identical to that for the MOBILE BAY.

The analysis of the self-propulsion data from the MOBILE BAY trials indicated that the value of K_Q in ice was generally constant. It was approximately equal to the bollard condition value. In open water K_Q decreases with ship advance coefficient, J_s. A dispersion of the data coincident with increasing ice thickness is observed.

The corresponding K_T values in ice are shifted upwards by a constant from the open-water curve. The decline in K_T with J_s has the same slope as the open-water curve and shows no dependence on ice thickness. It is therefore recommended that calculations of propeller advance velocity and wake fraction should use the shaft thrust identity method rather than torque identity. Figure 3 shows the K_Q and K_T results.

The K_Q results are in good agreement with recent model tests at CRREL in pre-cut urea ice (Tatinclaux 1986). For the extreme fragment size of model ice, there was an upward trend of K_Q with J_s, but it is not expected that such large piece sizes would be encountered in full scale icebreaking. The full scale constant trend with J_s was most closely approximated in the model tests with brash ice.

The thrust deduction factor in ice, t_i, was shown to depend strongly on ice thickness decreasing from 0.5 to zero over the range of thickness tested. A plausible explanation for the smaller thrust deduction in thicker ice is that the hydrodynamic effects at any speed are relatively constant and therefore have a diminished importance as the ice loading increases. At lower speeds and in thinner ice it is postulated that t_i is affected by the presence of the propeller slip stream and its corresponding low pressure region. The slipstream during self-propelled tests is believed to draw more ice pieces under the hull and into the propeller than occurs during towed tests. This mechanism increases frictional resistance and decreases thrust.

No significant variation in thrust deduction with velocity was identified. However the advance coefficient range was not large. Thrust deduction declines with increasing ice thickness towards the open water bollard value, which is nearly zero. In the present trials there are no large magnitude propeller-ice interactions appearing in the thrust and torque time histories. Hence the specific influence of ice milling is not assessed, although the severity of ice ingestion has been investigated.

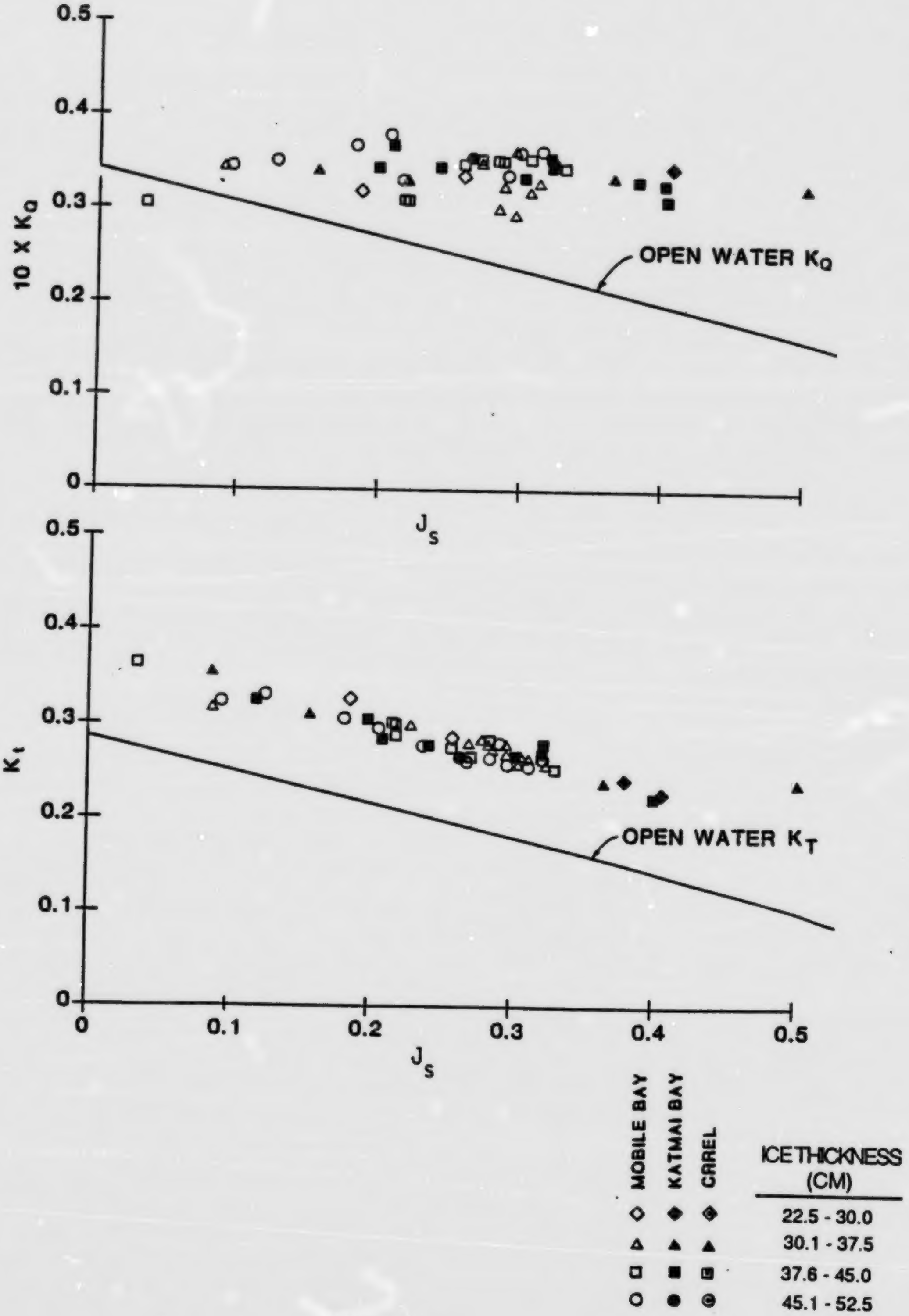


Figure 3
MOBILE BAY PROPELLER PERFORMANCE CURVES AND COMPARISON TO OPEN WATER PREDICTIONS

Wake fraction, v_i, was observed to decrease from very large values at the bollard condition and to approach a constant value of approximately 0.5 at increasing values of ship advance coefficient. The large values of wake fraction are surprising in comparison to typical clear water values but they are in general agreement with other icebreaking test results reported in the literature. However these results depend on the use of thrust identity methods and open-water propeller data, and therefore they should be interpreted cautiously subject to further examination of the effects of propeller loading and ice interaction.

The quasi-propulsive efficiency in ice has been divided into hull efficiency, relative rotative efficiency and open-water efficiency components. The relative rotative efficiency was well behaved and varied with J_s. No dependence on ice thickness was identified for the relative rotative component. The hull efficiency term was not well behaved. It is formed from the ratio of thrust deduction factor ($1 - t_i$) and wake factor ($1 - v_i$). The latter goes to zero where wake fraction equals one and therefore hull efficiency is undefined. Consequently it is more reasonable to consider t_i and v_i separately.

Only a severely limited set of urea ice model test data, consisting of six data points, was available as a basis for comparison to the trials propulsion results. Nonetheless it is clearly seen that the model data does not adequately predict the full scale propulsion coefficients. Both wake fraction and thrust deduction are underestimated. Quasi-propulsive efficiency and relative rotative efficiency are somewhat closer. This poor prediction likely results from a combination of scale effects involving density, hull-ice friction, piece size distribution, and crushing strength. Figure 4 and Figure 5 show comparisons between model and full scale results for thrust deduction fraction and wake fraction respectively.

The conclusions form the basis for a range of recommendations for further work which include expanding the full scale resistance and self-propulsion data base; improving the analysis procedures for predicting icebreaker performance; and standardizing model test procedures by assessment of the sensitivity of the factors influencing resistance and propulsion in different ice materials. In particular:

- Participation with the U.S. Maritime Administration in a second generation of towed resistance trials of the MOBILE BAY would be advantageous, if carried out in thinner ice and over an extended advance coefficient range. Additional full scale towed tests in clear water would enhance the overall value of the present data set.

- The influence on resistance measurements of pressure relief in the ice caused by the towing vessel should be further investigated. This may be accomplished by conducting tests in a manner which avoids the formation of a broken channel parallel to the MOBILE BAY track. An alternative method involves a detailed comparison between thrust values for self-propulsion trials in a track with pressure relief and trials without pressure relief.

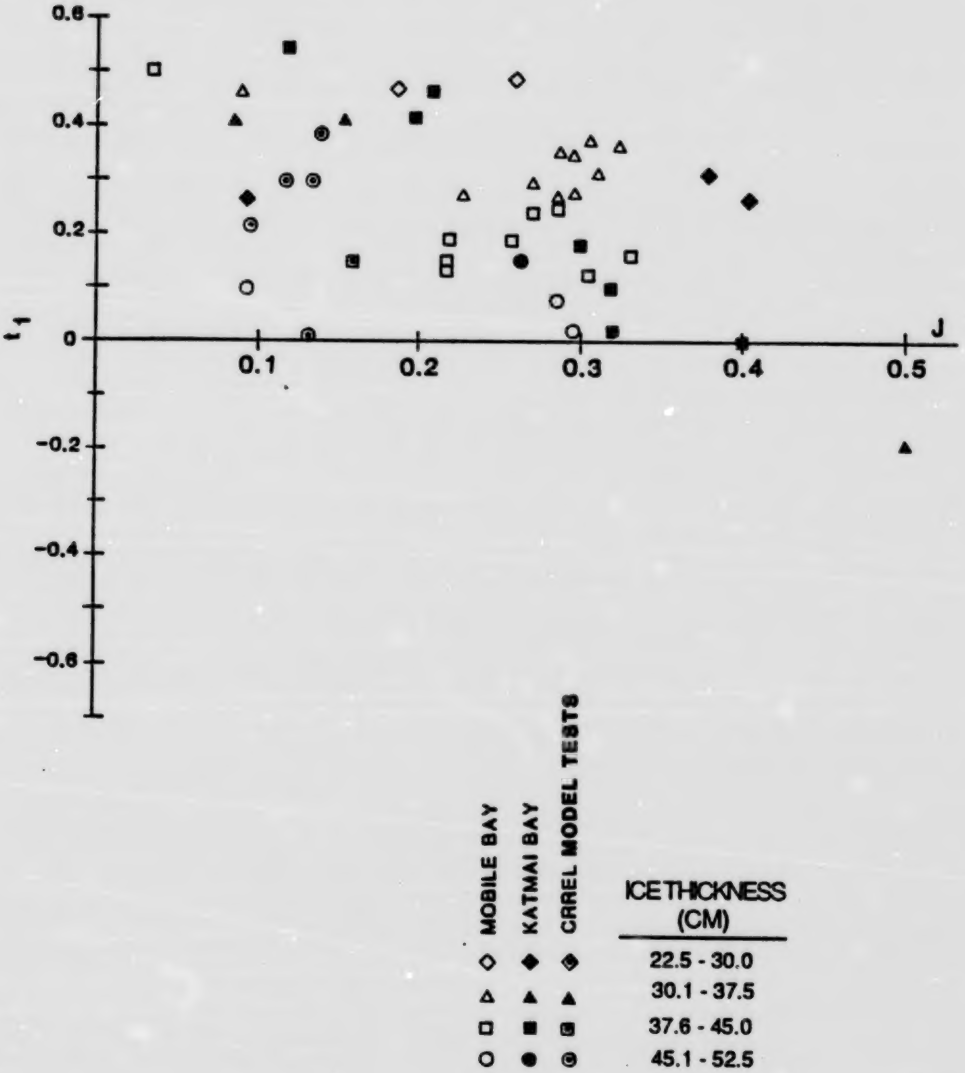


Figure 4

THRUST DEDUCTION (t1) COMPARISON TO KATMAI BAY AND CRREL RESULTS

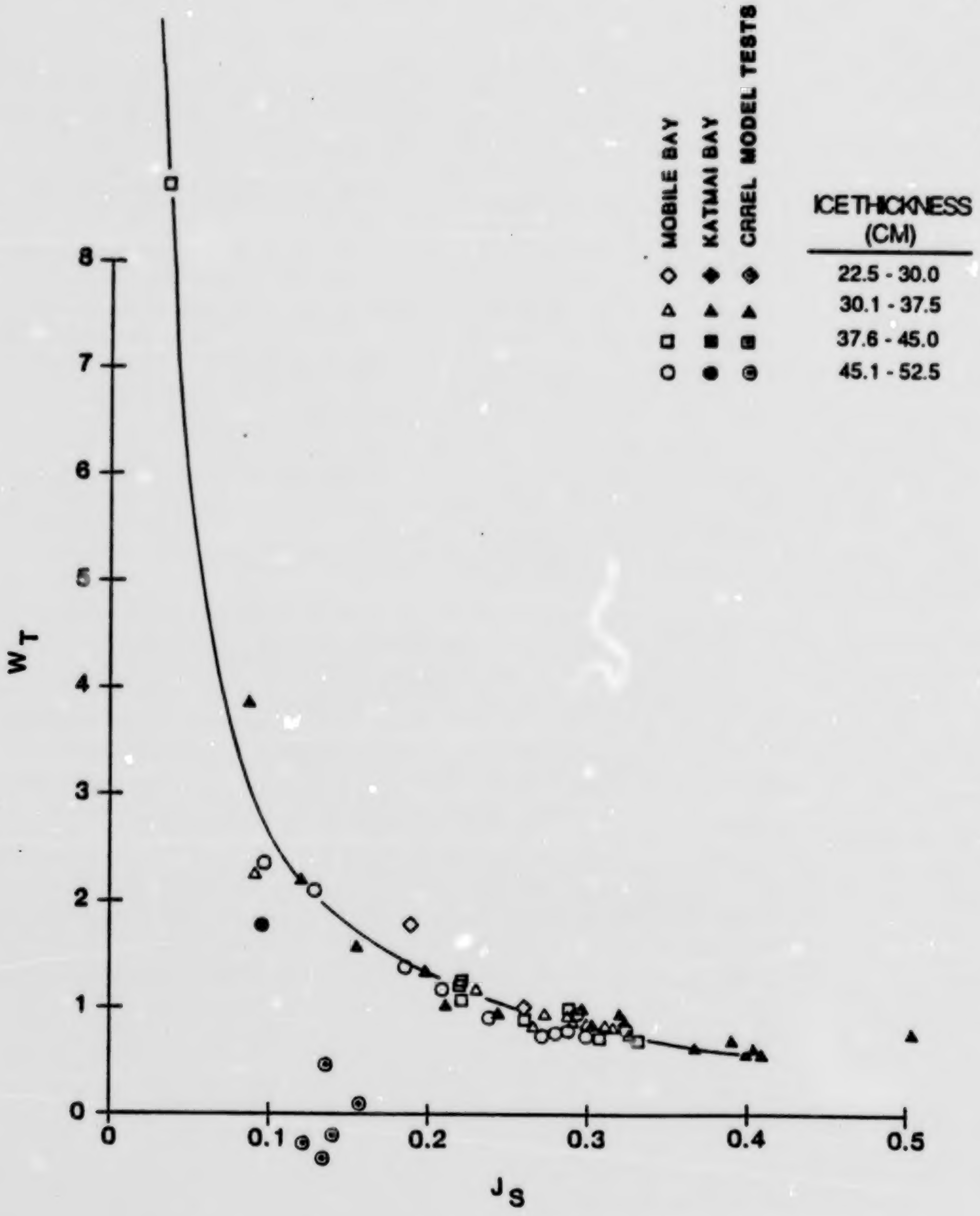


Figure 5

WAKE FRACTION COMPARISON TO KATMAI BAY AND CRREL RESULTS

° The MOBILE BAY resistance data is unique and offers the rare opportunity to fully characterize an icebreaking hull form. To maximize the technical benefits from these trials requires a follow-up program of model tests which systematically assesses the concerns identified in the comparison of full scale and model scale results. In view of the differences in performance attributed to hull-ice friction coefficient, density, ice strength and elastic modulus, the test program should utilize all available ice modelling materials. It is recommended that the resistance and self-propulsion tests be carried out in both level ice and in a range of pre-cut ice sizes, and include bow motions. In addition, the ship-ice interaction forces should be measured for the same test conditions. A separate investigation of propeller-ice interaction should address the influence of various ice parameters on the propulsive coefficients. Overload propeller tests should be considered a priority in any future experimental program.

° Despite many years of practical ice basin experience, it appears that physical modelling of the icebreaking process remains inadequate to predict propulsive performance. It is believed that improvements in performance prediction can be achieved, but require renewed research into the physical mechanisms involved in the icebreaking process. In particular, the effectiveness of different types of model ice should be examined thoroughly.

° In many respects the WTGB program parallels and supplements the R-Class work being carried out in Canada and at various International Towing Tank facilities; and the results should be coordinated. The influence of hull form geometry and other parameters cannot be evaluated from a study of only one vessel and therefore it would be advantageous to test other models under the same controlled conditions as recommended for MOBILE BAY.

SOMMAIRE

Ce rapport donne les résultats des essais de traction et d'autopropulsion faits à bord du remorqueur brise-glace MOBILE BAY de la Garde côtière des Etats-Unis. Effectués dans une glace uniforme, dans la partie septentrionale de Green Bay du lac Michigan, ces essais avaient pour but de constituer une base de données à partir de laquelle il serait possible de prévoir les performances des navires dans les glaces. Ce programme a été parrainé conjointement par la Garde côtière des Etats-Unis, l'U.S. Maritime Administration et Transports Canada (Centre de développement des transports). L'objectif premier était d'obtenir des mesures en vraie grandeur de bonne qualité en ce qui concerne:

- o la résistance aux essais de traction dans des glaces uniformes et intactes;
- o la résistance en autopropulsion dans des glaces uniformes;
- o l'épaisseur et la résistance à la rupture en flexion des glaces.

Le MOBILE BAY appartient à la classe des remorqueurs hors mer appelés "WTGC 140 pieds", allusion faite à la forme de leur carène et à leur longueur à la ligne de flottaison. Le rôle de navire tracteur et de base des opérations a été tenu par le USCGC MACKINAW.

Une chaîne de mesure sophistiquée avait été placée à bord du MOBILE BAY pour enregistrer les données et assurer le suivi des opérations de traction. Après la localisation d'un champ de glaces uniformes convenant aux essais, ceux-ci ont été entrepris en février 1986 par les responsables du projet. La température étant au beau, ces essais ont été menés rondement. La présence de glaces dont l'épaisseur a varié beaucoup plus que prévu a enrichi d'autant les résultats de cette campagne de mesurage qui a porté sur les paramètres suivants: poussée, couple, régime de rotation de l'hélice, vitesse et effort de traction. Les données obtenues se sont avérées cohérentes et de bonne qualité. Une récapitulation en est faite au tableau 1.

Résistance globale

Les résultats les plus intéressants ont été les données sur la résistance à la marche dans des conditions variées de vitesse de marche et d'épaisseur de glaces. Ils constituent une base de données unique en son genre, qui permettra une révision rationnelle des techniques de prévision des performances.

Résistance des glaces

La résistance des glaces a été obtenue en défalquant de la résistance globale la résistance en eau libre théorique, cette dernière étant tirée d'essais sur modèle réduit, à défaut de données réelles. Dans l'analyse numérique des données sur la résistance des glaces, il a été procédé à une évaluation approfondie des paramètres sans dimensions et des diverses relations mathématiques empiriques utilisées dans des recherches antérieures. Il s'est avéré que l'équation empirique qui cerne de plus près les données obtenues est la suivante:

$$R_i/p_w gBh^2 = 4{,}254 + 3{,}963 \times 10^{-5}\ (V/\sqrt{gB})^2\ (L/h)^3$$

TABLEAU 1

SOMMAIRE DES RESULTATS

ESSAIS DE TRACTION

Nombre de points caractéristiques: 17

Fourchette des vitesses: 1,1 à 7,6 noeuds

Fourchette des épaisseurs: 32 à 52 cm (moyenne 40,4 cm)

Fourchette des résistances: 49 000 à 169 000 N
11 000 à 37 000 lb

ESSAIS D'AUTOPROPULSION

Nombre de points caractéristiques: 31

Fourchette des vitesses: 0,4 à 6,8 noeuds

Fourchette des épaisseurs: 26.7 à 48,3 cm

Fourchette des puissances fournies: 400 à 2 500 Hp sur l'arbre (300 à 1 900 kW)

RESISTANCES DES GLACES

Nombre de points caractéristiques: 14

Résistance moyenne: 454 kPa

Fourchette des résistances: 283 à 648 kPa

Taux de déformation moyen: $\frac{7,3 \times 10^{-3}}{\text{sec}}$

La figure 1 compare cette équation (E) tirée des essais de traction à plusieurs autres formules de prévision tirées des essais sur modèle réduit des WGTB et d'autres sources; elle donne une corrélation de 0,96. Il faut cependant relever l'étroitesse de la fourchette des valeurs d'épaisseur des glaces observées et les variations trop faibles de ce paramètre pour pouvoir déterminer l'influence de la résistance à la rupture en flexion. Une recherche plus approfondie est donc nécessaire pour affiner cette équation et en généraliser la portée.

Les essais de traction ont confirmé les résultats antérieurs (Tatinclaux-1984), selon lesquels la résistance du modèle serait de beaucoup supérieure à la résistance réelle (figure 2). Un nouvel examen des données tirées des essais dans une glace modèle à l'urée et une autre à l'eau salée, effectués respectivement dans le Cold Regions Research and Engineering Laboratory (West-1975) et dans le bassin d'Arctec (Lecourt-1975), a montré que la résistance dans la glace à l'eau salée est plus proche de la résistance réelle que celle dans la glace à l'urée.

Les chercheurs ont mis en évidence un certain nombre de facteurs susceptibles de déformer les résultats tant réels que sur modèle. Ils avaient d'abord cru que le chenal pratiqué par le MACKINAW en vue des essais de traction du MOBILE BAY pouvait avoir eu pour effet de délester celui-ci d'une partie de la pression normale des glaces, d'où une réduction de la résistance mesurée. Toutefois, l'analyse des résultats d'autopropulsion n'a montré aucune variation substantielle entre les valeurs de poussée correspondant, d'une part, aux essais en champ de glace intact et, d'autre part, aux essais marqués par l'existence d'un chenal ouvert parallèlement au tracé suivi par le MOBILE BAY. Ce qui porte à croire que les écarts entre les résultats réels de fonction et ceux sur modèle ne peuvent pas être attribués à la présence ou à l'absence de chenal parallèle. On serait plutôt porté à croire que les résultats sur modèle ont été influencés par des variations dans le coefficient de frottement coque-glaces, la densité relative de la glace modèle utilisée et le mécanisme précis de rupture de celle-ci (voir annexe A).

La constatation que la résistance sur modèle est supérieure à la résistance en vraie grandeur était attendue, vu que c'est généralement ce qui se produit. Cet état de choses peut s'expliquer par la procédure habituellement suivie dans les études sur modèle en bassin d'essais des carènes. Les chercheurs retiennent des valeurs de résistance et de frottement trop élevées, qu'ils corrigent ensuite en faisant intervenir un facteur de correction adimensionnel. Or, rien dans les résultats obtenus ici ne justifiait la prise en compte d'un tel facteur.

L'écart constaté entre les résultats des essais dans la glace à l'eau salée et ceux obtenus dans la glace à l'urée a mené à l'idée que les glaces modèles généralement utiles en bassin réfrigéré ont une résistance à l'écrasement mal calculée et que cela pourrait être un facteur déterminant à l'origine des erreurs dans les prévisions de résistance. En se basant sur les essais sur modèle réduit du N.M. Arctic (Phillips-1986) et sur leur corrélation avec les essais réels, les chercheurs ont défini une relation de similitude concernant le rapport pression - surface, qui mène à une valeur de résistance à l'écrasement beaucoup plus faible.

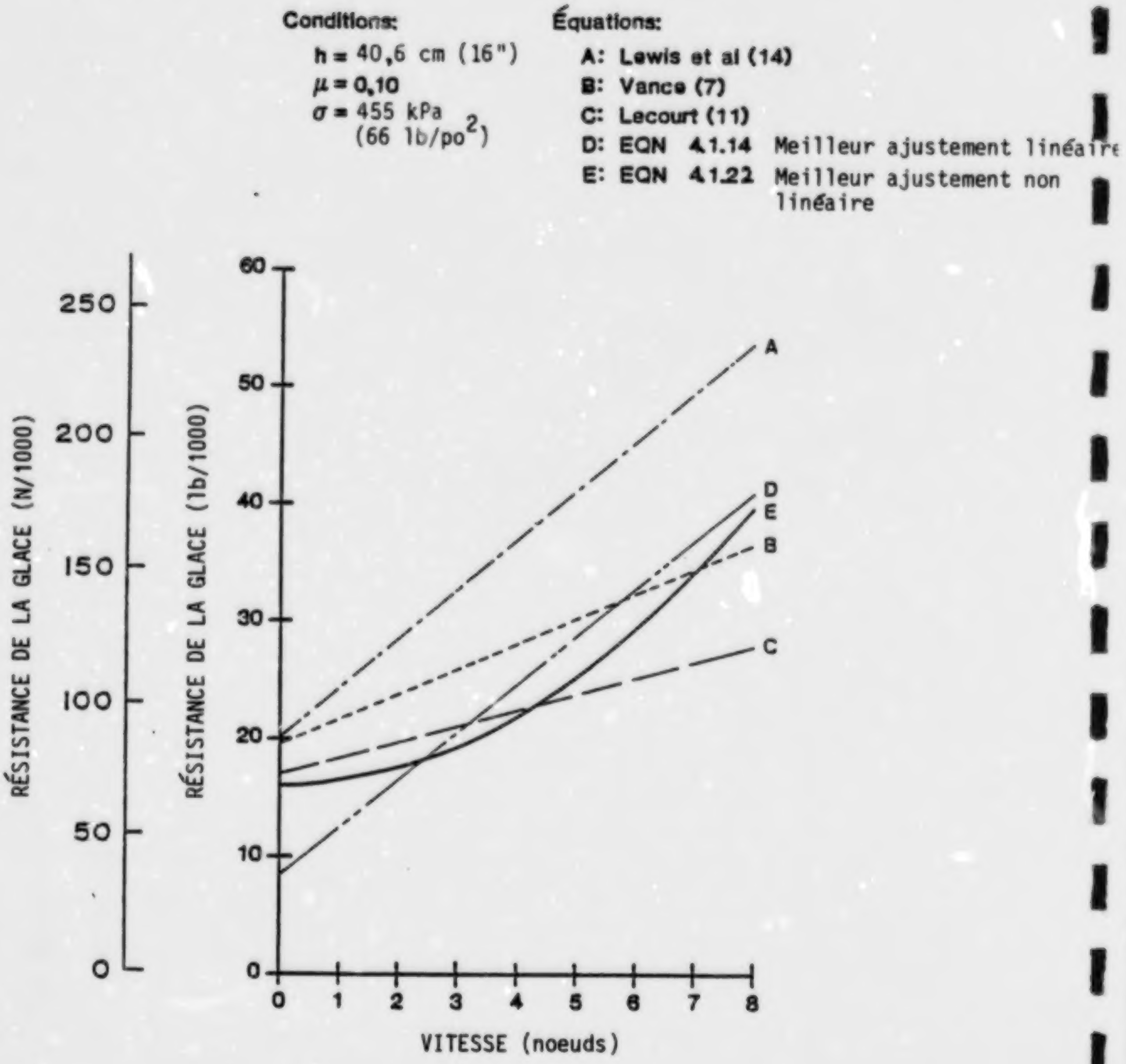


Figure 1

RESISTANCE CALCULÉE À L'AIDE DES DIVERSES ÉQUATIONS EMPIRIQUES

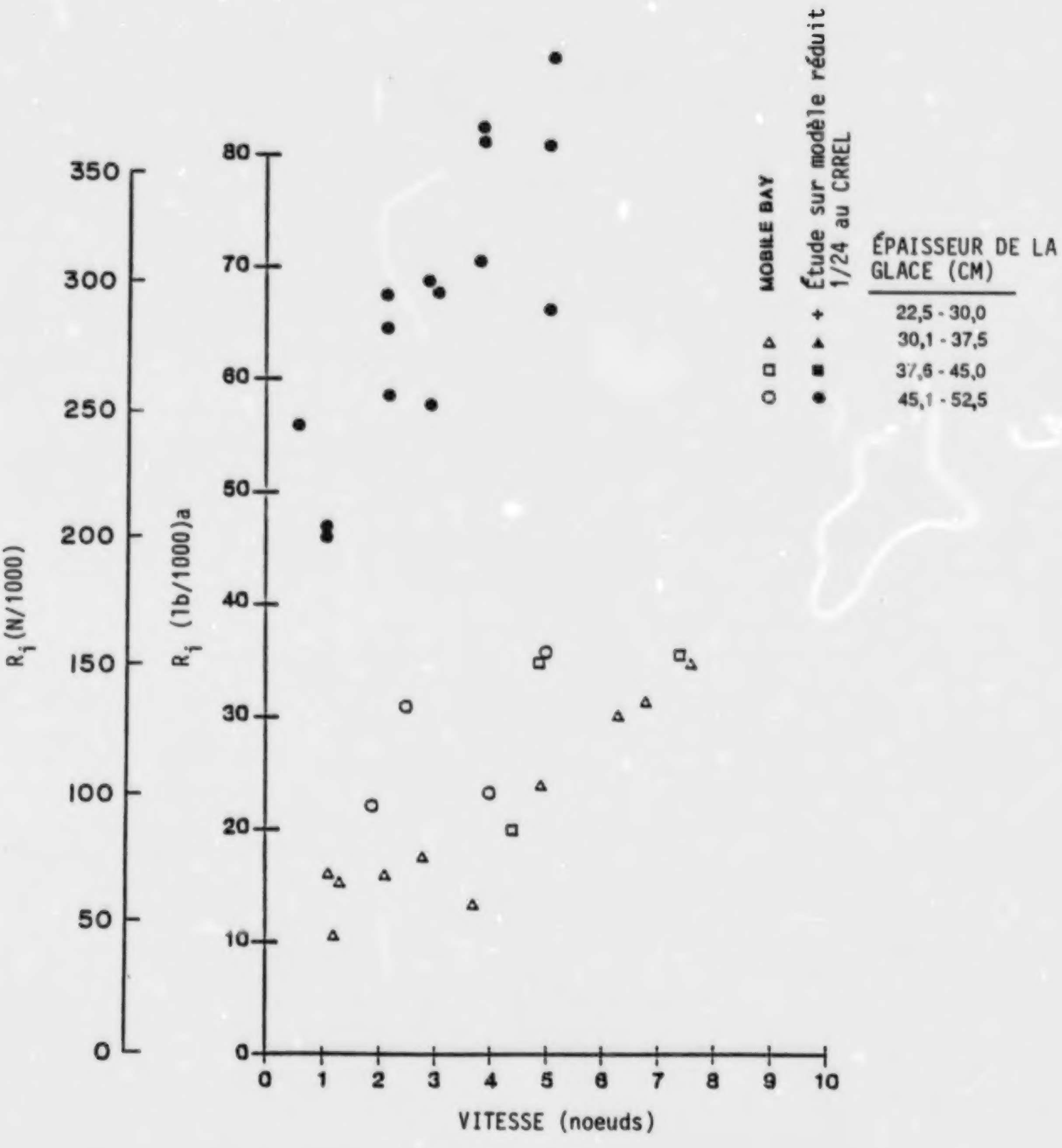


Figure 2

COMPARAISON DES RÉSULTATS RÉELS (MOBILE BAY)
AVEC CEUX DE L'ÉTUDE SUR MODÈLE 1/24 AU CRREL

Essais d'autopropulsion

En 1979, le N.M. KATMAI BAY, un remorqueur identique, avait été soumis à des essais d'autopropulsion dans des conditions glacielles similaires, donnant des résultats concordant bien avec ceux du MOBILE BAY pour ce qui est de K_T, K_Q et du coefficient de sillage. De même, lorsque les chercheurs se sont servis de l'équation de résistance à la marche du MOBILE BAY afin de calculer le coefficient de succion propre au KATMAI BAY, celui-ci s'est avéré virtuellement identique à celui du MOBILE BAY.

L'analyse des résultats des essais d'autopropulsion du MOBILE BAY a montré que, dans les glaces, K_Q ne varie pas et qu'il est à peu près égal à la valeur au point fixe. En eau libre, K_Q évolue à la baisse par rapport à J_s, coefficient de translation navire. Une dispersion des résultats a été observée, augmentant avec l'épaisseur.

Par rapport aux valeurs correspondantes en eau libre, les valeurs de K_T dans les glaces sont décalées vers le haut par un facteur fixe; toutefois, la pente descendante de K_T en fonction de J_s est la même qu'en eau libre, ce qui montre que ce paramètre ne subit pas l'influence de l'épaisseur des glaces. Il est donc recommandé que, pour calculer la vitesse de translation hélice et le coefficient de sillage, on ait recours à la méthode dite "S et T" et non pas à celle du "TI". La figure 3 donne les résultats de K_Q et K_T.

Les valeurs de K_Q concordent bien avec celles tirées d'essais sur modèle réduit faits récemment au laboratoire CRREL dans une glace à l'urée préentaillée (Tatinclaux-1986). K_Q tend à augmenter avec J_s pour les plus gros fragments de glace modèle, mais il est peu probable que dans la réalité les fragments atteignent des dimensions comparables. La stabilité de J_s dans les glaces en vraie grandeur a été le plus approchée lors des essais sur maquette dans une glace modèle de type bourguignon.

Le coefficient de succion dans les glaces, t_i, s'est révélé fortement tributaire de l'épaisseur des glaces, fléchissant de 0,5 à zéro dans l'intervalle des épaisseurs en jeu. Une explication plausible de la relation inverse coefficient de succion-épaisseur serait que l'effet hydrodynamique demeure relativement constant quelle que soit la vitesse et que, conséquemment, son importance diminue à mesure que la charge des glaces croît. Aux faibles vitesses et dans une glace fine, t_i serait influencé par l'existence du courant provoqué par l'hélice et par la dépression qui en résulte. On croit savoir que, dans les essais d'autopropulsion, les fragments de glace entraînés sous la coque et franchissant le cercle de rotation de l'hélice sont plus nombreux que lors des essais de traction, provoquant une résistance de frottement accrue et une diminution de la poussée.

Aucune variation notable de la succion n'a été constatée par rapport à la vitesse. A noter cependant l'étroite fourchette du coefficient de translation. A mesure que l'épaisseur augmente, la succion tend vers une valeur proche de zéro, qui est celle du point fixe en eau libre. Les courbes de poussée et de couple en fonction du temps n'ont fait ressortir aucune interaction hélice-glace de quelque importance, d'où l'impossibilité d'évaluer l'influence particulière du broyage des glaces, malgré le fait qu'on se soit penché sur ce phénomène.

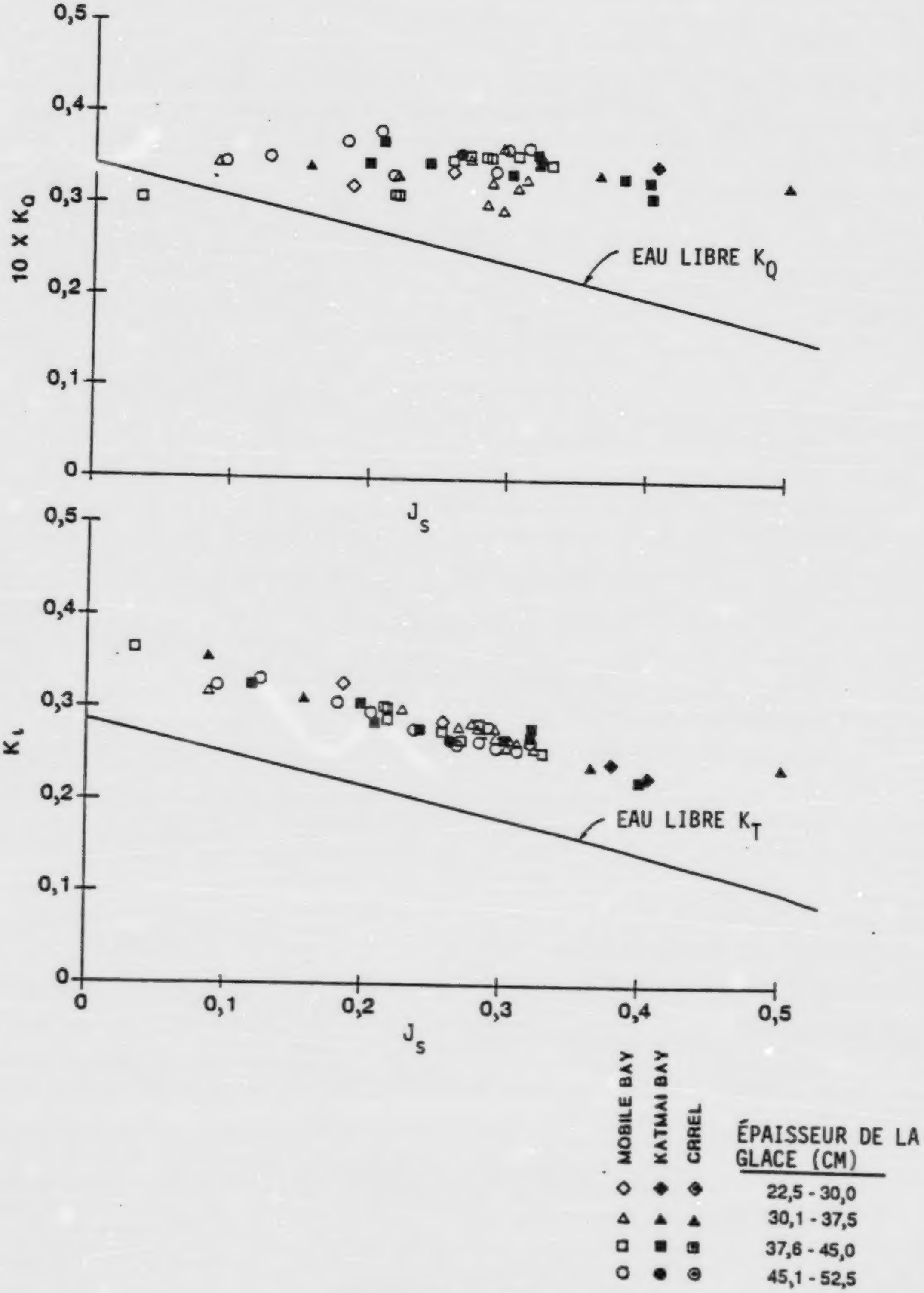


Figure 3

COMPARAISON DES RENDEMENTS PROPULSIFS DU MOBILE BAY
AVEC LES PRÉVISIONS EN EAU LIBRE

Le coefficient de sillage, w_i, prend une allure qui décroît depuis des valeurs très élevées au point fixe vers une valeur constante autour de 0,5 à mesure qu'augmente le coefficient de translation navire. Les valeurs élevées de ce coefficient sont surprenantes comparativement aux valeurs type en eau libre, mais, par ailleurs, elles concordent avec les résultats déjà publiés en ce qui concerne d'autres brise-glace. Toutefois, comme ces résultats sont tirés des méthodes dites "Thrust Identity" et de données sur le comportement des hélices en eau libre, ils restent sujets à caution tant qu'une étude plus approfondie de l'influence de la charge d'hélice et de l'interaction dynamique des glaces n'aura pas été faite.

Le pseudo-rendement propulsif dans les glaces a été décomposé en rendement de carène, rendement d'adaptation de l'hélice et rendement en eau libre. La courbe du rendement d'adaptation évolue de manière stable par rapport à J_s et ne montre aucun lien par rapport à l'épaisseur des glaces. Par contre, l'allure du rendement de carène est difficile à cerner. Ce rendement est le quotient du coefficient de poussée corrigé $(1 - t_i)$ par le terme $(1 - w_i)$. Ce dernier terme a une valeur de zéro lorsque w_i est égale à l'unité, laissant indéfini le rendement de carène. Il serait plus logique de considérer t_i et w_i comme des entités séparées.

Pour comparer les rendements propulsifs issus des essais sur modèle réduit à ceux des essais en vraie grandeur, les chercheurs ne disposaient que de six points caractéristiques concernant les essais en glace à l'urée. Néanmoins, il est clair que ces rendements ne donnent pas une bonne approximation des valeurs correspondantes en vraie grandeur. Le coefficient de sillage et la succion sont tous deux sous-estimés, alors que les rendements pseudo-propulsif et d'adaptation serrent d'un peu plus près la réalité. La médiocrité des prévisions serait attribuable au manque de similitude dans des facteurs tels que densité relative, frottement coque-glace, distribution dimensionnelle des fragments et résistance à l'écrasement. Les figures 4 et 5 comparent les résultats des études sur modèle aux résultats réels, pour ce qui est des coefficients de succion et de sillage, respectivement.

Conclusions

Les conclusions auxquelles les chercheurs sont arrivés leur ont permis de formuler plusieurs recommandations concernant les travaux complémentaires à réaliser, notamment: l'élargissement de la base de données concernant les essais de traction et d'autopropulsion; l'affinement des méthodes d'analyse et de prévision des performances et la standardisation des méthodes d'essais sur modèle en mettant en évidence la sensibilité des paramètres de résistance à la marche et de rendement propulsif aux divers types de glaces utilisées. Plus particulièrement:

- Participation, avec l'U.S. Maritime Administration, à un deuxième programme d'essais du MOBILE BAY, à condition que ceux-ci se fassent dans une glace moins épaisse et dans une fourchette plus étendue de coefficients de translation. Des essais complémentaires de traction en vraie grandeur et en eau libre rehausseraient la valeur globale de la base de données.

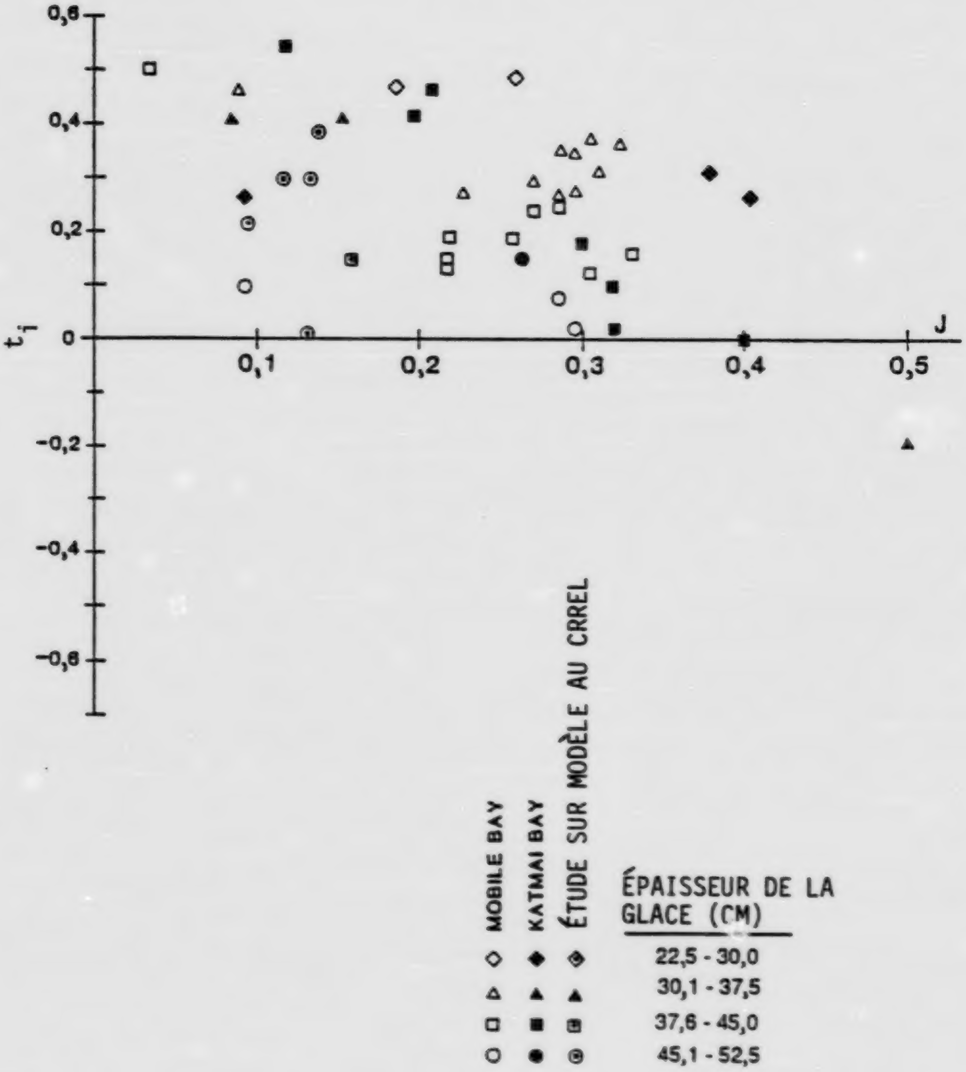


Figure 4

SUCCION (t_i) - COMPARAISON AVEC LES ÉTUDES À BORD DU KATMAI BAY ET AU CRREL

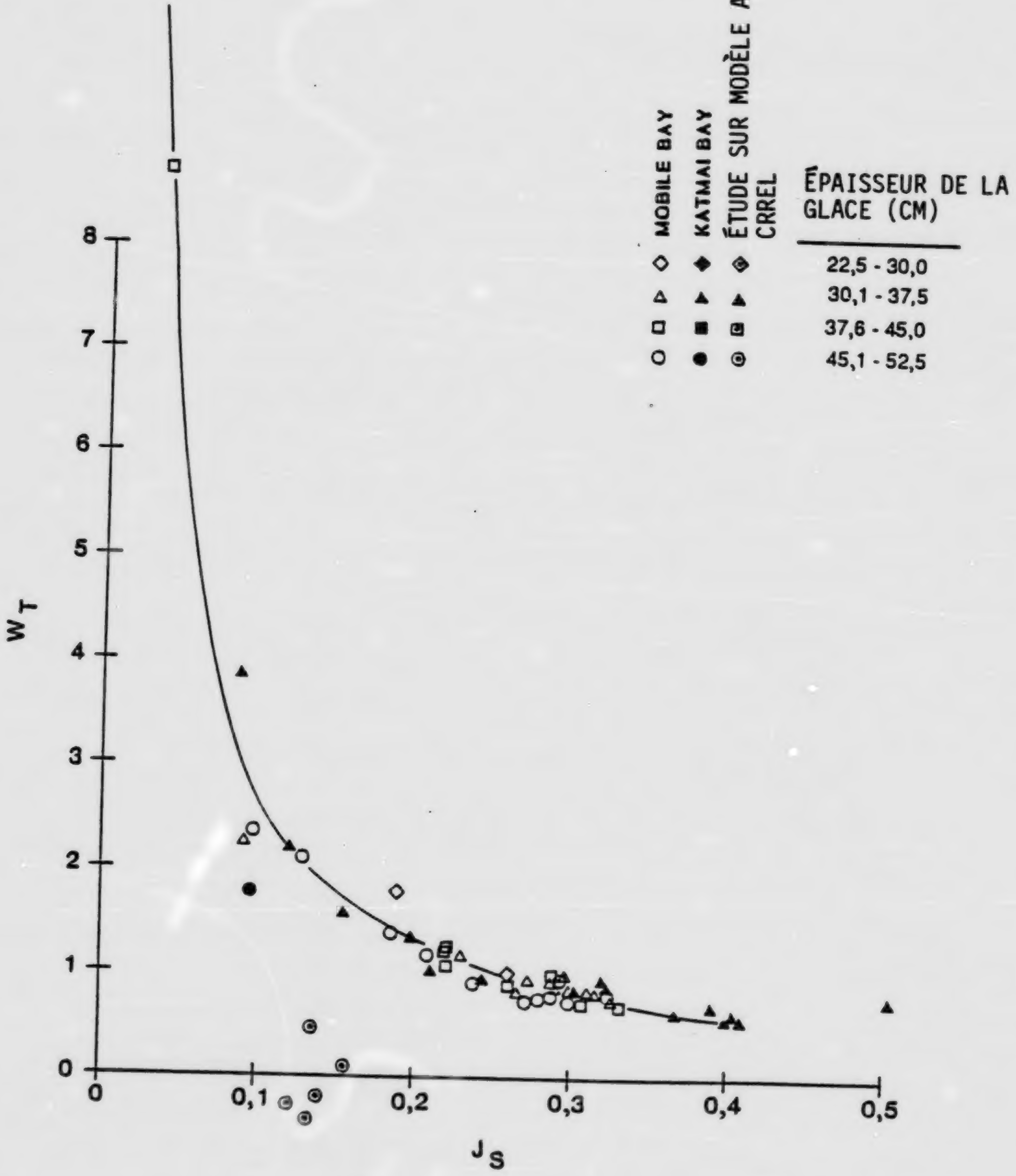


Figure 5

COEFFICIENT DE SILLAGE - COMPARAISON AVEC LES ÉTUDES À BORD DU KATMAI BAY ET AU CRREL

- Etude plus poussée de l'influence que peut avoir sur les mesures de résistance le délestage attribuable au navire tracteur. Pour cela, conduire les essais de façon à éviter qu'un chenal soit pratiqué parallèlement au tracé du MOBILE BAY. Une autre méthode consisterait à faire la comparaison détaillée des valeurs de poussée en autopropulsion avec et sans délestage.

- Base de données tirée des essais de traction du MOBILE BAY, présentant ceci de particulier qu'elle donne l'occasion unique de caractériser exhaustivement une forme de coque brise-glace. En vue de tirer tout le parti possible des essais effectués, il faudrait lancer un programme d'études complémentaires sur modèle qui approfondirait méthodiquement les écarts mis en évidence entre les résultats réels et les essais sur modèle réduit. Eu égard aux écarts de performances attribuables aux facteurs comme le coefficient de frottement coque-glace, la densité relative, la résistance des glaces et le module d'élasticité, ce programme d'essais devrait se faire dans tous les types de glace modèle connus. Il est recommandé: de conduire les essais de traction et d'autopropulsion d'abord dans un champ de glace uniforme et intacte, puis dans un champ préentaillé pour donner des fragments de tailles diverses, tout en imprimant des mouvements à l'avant de la maquette; conduire des études corollaires sur l'interaction dynamique coque-glaces, dans les mêmes conditions d'essai; enfin, il est recommandé de faire une étude distincte sur l'interaction hélice-glace dans le but de mettre en évidence l'influence des diverses propriétés des glaces sur les divers facteurs du rendement propulsif. Les essais en régime de surcharge devraient figurer au premier rang de toute expérimentation ultérieure.

- Malgré la longue pratique des bassins d'essais des carènes, la physique de la rupture des glaces par un brise-glace débouche sur des prévisions de rendement propulsif erronées. Des résultats bien meilleurs peuvent être obtenus à la condition de pousser la recherche sur le mécanisme de rupture, et notamment sur les propriétés des différentes glaces-modèles.

- A plusieurs égards, le programme WTGB reprend en les complétant les travaux faits au Canada sur les brise-glace de classe R ainsi que dans divers bassins d'essais des carènes étrangers. Tous ces travaux devraient être coordonnés. Comme l'influence de la forme de carène et d'autres paramètres ne peut ressortir de l'étude d'un seul navire, il faudrait que les essais d'autres modèles de navire se fassent dans les mêmes conditions contrôlées que celles préconisées pour le MOBILE BAY.

TABLE OF CONTENTS

VOLUME 1

SECTION 1 INTRODUCTION..1

1.1 Overview..1
1.2 Background..1
1.3 Test Program Objectives..3

SECTION 2 TEST SET-UP AND OPERATIONS..7

2.1 Test Instrumentation..8
2.2 Self-propelled Test Procedures..17
2.3 Towed Test Procedures..20
2.4 Ice Strength Measurements..35
2.5 Log of Daily Activities..38

SECTION 3 TEST RESULTS..41

3.1 Towed Resistance Results..42
3.2 Self-Propelled Results..53
3.3 Ice Strength Results..61
3.4 Propeller-Ice Interaction..64

SECTION 4 ANALYSIS..68

4.1 Level Ice Resistance..70
4.2 Analysis of Self-Propulsion Results..100

SECTION 5 CONCLUSIONS AND RECOMMENDATIONS..140

SECTION 6 REFERENCES..147

VOLUME II

APPENDIX (i) WORK STATEMENT - TASK GROUP D

APPENDIX A - IMPLICATIONS FOR MODEL TEST METHODS

APPENDIX B - SHIP TRACKINGS FOR TOWED AND SELF-PROPELLED TESTS

APPENDIX C - TOWED TEST RESULTS

APPENDIX D - SELF-PROPELLED TEST RESULTS AND ANALYSIS

APPENDIX E - REGRESSIONS FOR LEVEL ICE RESISTANCE EQUATIONS

APPENDIX F - TEST INSTRUMENTATION

LIST OF FIGURES

1.2-1 PRINCIPAL PARTICULARS OF MOBILE BAY....................................4
1.2-2 LINES AND BODY PLAN OF MOBILE BAY.......................................5
1.2-3 OPEN WATER PROPELLER CHARACTERISTICS....................................6
2.1-1 BLOCK DIAGRAM OF INSTRUMENTATION AND DATA ACQUISITION HARDWARE..................................10
2.1-2 ARRANGEMENT OF SIGNAL PROCESSING EQUIPMENT ON BRIDGE OF MOBILE BAY.................................14
2.1-3 ARRANGEMENT OF MONITOR EQUIPMENT ON MACKINAW AND MOBILE BAY...16
2.2-1 PLAN FOR SELF PROPELLED TESTS ON 2/24/86...............................18
2.2-1 ACTUAL TEST TRACKS OBSERVED ON RADAR FOR 2/24/86.......................19
2.3-1 FOREDECK ARRANGEMENT..21
2.3-2 TRACING OF TEST TRACK FROM MOBILE BAY'S RADAR..........................33
2.4-1 FLEXURAL STRENGTH APPARATUS...37
3.1-1A-E REPRESENTATIVE TOWING DATA...46
3.1-2 POSSIBLE MASS-SPRING ANALOGY..47
3.1-3 FULL SCALE TOWED RESISTANCE TEST TOW 6..................................49
3.1-4 FULL SCALE TOWED RESISTANCE TEST TOW 6..................................50
3.1-5 FULL SCALE TOWED RESISTANCE TEST TOW 6..................................51
3.1-6 FULL SCALE TOWED RESISTANCE TEST TOW 6..................................52
3.2-1 RAW DATA FOR SELF PROPELLED TEST SP-17(2/24/86).........................55
3.2-2 SELF PROPELLED TESTS SP 17..57
3.2-3 SELF PROPELLED TESTS SP 17..58
3.2-4 SELF PROPELLED TESTS SP 17..59
3.2-5 SELF PROPELLED TESTS SP 17..60
3.3-1 TYPICAL BEAM TEST TRACE (BEAM 10 2/24/86)...............................62
3.4-1 FULL SCALE TOWED RESISTANCE TEST..65
4.-1 ANALYSIS PROCEDURES...69
4.1-1 CURVE FIT USED FOR OPEN WATER RESISTANCE................................72
4.1-2 REGRESSION LINE FOR FINAL RESISTANCE FORM...............................80
4.1-3 MEASURED RESISTANCE FOR MOBILE BAY FROM TOWED TRIALS....................84
4.1-4 COMPARISON OF MOBILE BAY AND KATMAI BAY TEST DATA.......................85
4.1-5 COMPARISON OF MOBILE BAY DATA WITH CRREL 1:24 SCALE MODEL...86
4.1-6 COMPARISON OF MOBILE BAY DATA WITH CRREL 1:10 SCALE MODEL...87
4.1-7 COMPARISON OF MOBILE BAY DATA WITH ARCTEC LOW FRICTION MODEL..93
4.1-8 COMPARISON OF MOBILE BAY DATA WITH ARCTEC HIGH FRICTION MODEL..94
4.1-9 RESISTANCE ESTIMATES USING EMPIRICAL EQUATIONS.........................96
4.2-1 MOBILE BAY PROPELLER PERFORMANCE CURVES AND COMPARISON TO OPEN WATER PREDICTIONS..................102
4.2-2 THRUST DEDUCTION T_1 VARIATION WITH ICE THICKNESS...................106
4.2-3 THRUST DEDUCTION T_2 VARIATION WITH ICE THICKNESS...................106
4.2-4 DEFINITION SKETCH FOR THRUST IDENTIFY METHOD...........................109
4.2-5 WAKE FRACTION VARIATION WITH SHIP ADVANCE COEFFICIENT..................111
4.2-6 DEFINITION SKETCH FOR PROPELLER ADVANCE VELOCITY IN LOADED CONDITION...................................112
4.2-7 QUASI-PROPULSIVE EFFICIENCY (ND1) VARIATION WITH SHIP ADVANCE COEFFICIENT..........................114

4.2-8 QUASI-PROPULSIVE EFFICIENCY (ND2) VARIATION WITH SHIP ADVANCE COEFFICIENT....114
4.2-9 QUASI-PROPULSIVE EFFICIENCY (ND1) VARIATION WITH J_S H/D....115
4.2-10 QUASI-PROPULSIVE EFFICIENCY (ND2) VARIATION WITH J_S H/D....115
4.2-11 QUASI-PROPULSIVE EFFICIENCY (ND1) VARIATION WITH J_S H/D (DEGREE 2 REGRESSION FIT)....117
4.2-12 QUASI-PROPULSIVE EFFICIENCY (ND2) VARIATION WITH J_S H/D (DEGREE 2 REGRESSION FIT)....117
4.2-13 RELATIVE ROTATIVE EFFICIENCY VARIATION WITH SHIP ADVANCE COEFFICIENT....122
4.2-14 RELATIVE ROTATIVE EFFICIENCY VARIATION WITH J_S H/D....122
4.2-15 RELATIVE ROTATIVE EFFICIENCY VARIATION WITH KT....123
4.2-16 HULL EFFICIENCY (NH1) VARIATION WITH ICE THICKNESS....124
4.2-17 HULL EFFICIENCY (NH1) VARIATION WITH ADVANCE COEFFICIENT....124
4.2-18 THRUST DEDUCTION (ND1) COMPARISON TO KATMAI BAY AND CRREL RESULTS....126
4.2-19 WAKE FRACTION COMPARISON TO KATMAI BAY AND CRREL RESULTS...127
4.2-20 RELATIVE ROTATIVE EFFICIENCY COMPARISON TO KATMAI BAY AND CRREL RESULTS....132
4.2-21 QUASI-PROPULSIVE EFFICIENCY COMPARISON TO KATMAI BAY AND CRREL RESULTS....133

LIST OF TABLES

2.1-1 TEST SENSOR SUMMARY....11
3.1-1 TOWED TEST RESULTS....44
3.1-2 ICE THICKNESSES FOR TEST TOW-6....45
3.1-3 TEST RESULTS FOR TEST TOW-6....48
3.2-1 SELF-PROPELLED RESULTS....54
3.2-2 TEST RESULTS FOR TEST SP-178....56
3.3-1 ICE STRENGTH TEST SUMMARY....63
3.4-1 PROPELLER-ICE INTERACTIONS DURING TOWED TESTS....66
4.1-1 RESISTANCE FROM TOWED TESTS....73
4.1-2 NON-DIMENSIONAL NUMBERS USED IN ANALYSIS....75
4.1-3 SIMPLE CORRELATIONS FOR RESISTANCE DATA SET....75
4.1-4 SUMMARY OF FITTED RESISTANCE EQUATIONS....79
4.1-5 RESISTANCE DATA AVAILABLE FOR 140′ WTGB....83
4.1-6 RESISTANCE ESTIMATES FROM KATMAI BAY TRIALS....88
4.1-7 RESISTANCE ESTIMATES FROM CRREL 1:24 SCALE MODEL TESTS....89
4.1-8 RESISTANCE ESTIMATES FROM CRREL 1:10 SCALE MODEL TESTS....90
4.1-9 RESISTANCE ESTIMATES FROM ARCTEC MODEL TESTS: LOW FRICTION....91
4.1-10 RESISTANCE ESTIMATES FROM ARCTEC MODEL TESTS: HIGH FRICTION....92
4.1-11 COMPARISON OF RESISTANCE ESTIMATES FOR 140′ WTGB (BAY CLASS)....97
4.2-1A MOBILE BAY TRIALS: DIMENSIONLESS PROPULSIVE COEFFICIENTS...103
4.2-1B MOBILE BAY TRIALS: DIMENSIONLESS PROPULSIVE COEFFICIENTS...104
4.2-2 BREAKDOWN OF PROPULSIVE EFFICIENCY COMPONENTS SUMMARY SHEET....120
4.2-3 KATMAI BAY TRIALS DATA (1980)....128
4.2-4A REANALYSIS OF KATMAI BAY TRIALS DATA....129
4.2-4B CONTINUED....130
4.2-5 CRREL SELF PROPULSION DATA (BY INTERPOLATION)....131

LIST OF PLATES

2-1 TYPICAL GRAPHIC DISPLAY FROM ONBOARD DATA ACQUISITION SYSTEM....13
2-2 TYPICAL DISPLAY ON MACKINAW MONITOR....13
2-3 BOW VIEW OF MOBILE BAY SHOWING TOWING ARRANGEMENT....24
2-4 CLOSE-UP OF FISH-PLATE SHOWING LOAD SENSOR INSTALLATION....24
2-5 THIS VIEW SHOWS HOW ICE THREATENED THE PIN DURING RETRIEVAL....25
2-6 ARRANGEMENT PRIOR TO TEST WITH MOBILE BAY IN MACKINAW'S NOTCH....26
2-7 MOBILE BAY BACKING DOWN PRIOR TO TEST AFTER MAKING UP TOW....26
2-8 LINE PAYOUT AS MOBILE BAY BACKS AND MACKINAW MOVES AHEAD....27
2-9 MOBILE BAY IN POSITION ABEAM OF NOTCH IN THE SIDE OF THE TRACK....27
2-10 MOBILE BAY WORKING TO PORT AS MACKINAW MOVES FORWARD....28
2-11 AS CABLE IS PAYED OUT IT FALLS TO THE ICE TO PORT OF MACKINAW'S TRACK....28
2-12 MACKINAW CONTINUES TO DEPLOY CABLE AS SHE MOVES AHEAD....29
2-13 VIEW OF TRACKS BEFORE TEST AFTER CABLE IS FULLY DEPLOYED....29
2-14 PRIOR TO TOW ON-ICE MEASUREMENTS OF THICKNESS WERE MADE AND MARKERS PLACED....30
2-15 SERPENTINE CABLE SHAPE ON ICE PRIOR TO THE TOW....30
2-16 ACTUAL TOW THROUGH UNBROKEN LEVEL ICE....31
2-17 STRESS RELIEF CRACKS TO STBD OF MOBILE BAY GENERALLY ENDED DATA COLLECTION....31
2-18 RADAR VIEW OF TRACKS AFTER TEST....32
2-19 CHART RECORDER AND AMPLIFIERS FOR BEAM TESTS....36
2-20 CUTTING BEAMS USING CHAINSAW....36
2-21 BEAM SET UP WITH BEAM FLOATING AFTER A TEST....36

NOMENCLATURE

a	Constant
A	Subscript denoting 'propeller advance'
A_x	Midship Area
b	Constant
B	Maximum beam at operating waterline
Bi	Subscript denoting 'behind ship in ice'
B	Subscript denoting 'behind ship in open water'
C	Constant
C_1, C_2, C_3	Coefficient or Exponents in Regression Equations
D	Diameter of MOBILE BAY propeller
E	Ice elastic modulus
h	Ice thickness
H	Subscript denoting 'Hull'
J_s	Advance Coefficient of Ship
J_A, J_{Bi}	Advance Coefficient of Model Propeller
J_o	Open Water Propeller Advance Coefficient
K_Q	Torque Coefficient
K_T	Thrust Coefficient
L	Ship Length at operating waterline
n, n_{Bi}	RPM of propeller (per second)
o	Subscript denoting 'open-water condition'
P	Towline Pull at MOBILE BAY bow
Q, Q_o, Q_B, Q_{Bi}	Torque
r	Correlation coefficient of regression equation
r, Rt	Subscript denoting 'relative rotative'
R, R_{TOT}	Total Hull Resistance

R_{ice}, R_i	Pure Ice Resistance
R_{ow}	Clear-Water Resistance
t, t_1, t_2	Thrust deduction fraction. Subscripts denote resistance formulation in calculation.
T, T_{Bi}	Propeller thrust
V, V_s	Ship Velocity (knots)
V_A,	Advance Velocity of Propeller
V_{Bi}	Advance Velocity, Behind Pulling and Ice Conditions
w, w_t, w_{Bi}	Taylor (effective) wake fraction
α	Angle of attack
Δ	Ship weight displacement, also denotes small change in a variable following
σ, σ_f	Ice flexural strength
σ_c	Ice crushing strength
σ_Q	Standard Deviation of Torque Data
λ	Model scaling factor
η_B, η_{Bi}	Quasi-Propulsive Efficiency (in clear water or ice)
η_{D1}, η_{D2}	Quasi-Propulsive Efficiency (Calculated from Resistance form 1 or 2)
η_H	Hull Efficiency
η_o	Open Water Propeller Efficiency
η_{Rt}, η_r	Relative Rotative Efficiency
η_{HRPB}	Hull Efficiency Component due to overload pull
η_{RRPB}	Relative Rotative Efficiency Component due to overload pull
η_{HRiP}	Hull Efficiency Component due to ice effects
η_{RRiP}	Relative Rotative Efficiency Component due to ice effects
ρ_i	Mass density of ice

ρ_w	Mass density of water
ω	Hull/ice friction factor
∇	Ship volume displacement
ϕ	Pitch of propeller

ABBREVIATIONS

AGENCIES:

ACL	ARCTEC CANADA LIMITED
AEI	ARCTEC ENGINEERING INCORPORATED
CRREL	COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
TDC	TRANSPORTATION DEVELOPMENT CENTRE
USCGC	UNITED STATES COAST GUARD CUTTER

NOTE ON UNITS:

This study has been carried out jointly with the U.S. Maritime Administration and therefore Imperial units have been used in data collection and reduction. This edition of the report complies with the Transport Canada requirements for presentation of results in terms of S.I. units. All Tables and Figures have been converted to S.I. units and data in the text has been duplicated in both systems. However, some figures and appendices which show typical data in its computer generated form retain Imperial units and therefore the following set of conversions is provided:

Length (metres)	1 m = 39.36 inches
Force (Newtons)	1 N = 0.2248 lb_f
Stress (kilo Pascals)	1 kPa = 0.145 psi
Power (kilo Watts)	1 kW = 1.341 Hp
Speed (knots)	1 kts = 0.515 m/s = 1.689 ft/s

1. INTRODUCTION

1.1 Overview

Full-scale resistance towing trials of the United States Coast Guard Cutter MOBILE BAY were carried out in Great Lakes' ice during February 1986. The program was jointly sponsored by the USCG, U.S. Maritime Administration and Transport Canada (Transportation Development Centre). Its primary objectives were to obtain reliable full-scale measurements of:

- Towed resistance of MOBILE BAY in uniform level ice;
- Self-propelled performance of MOBILE BAY in level ice; and
- Ice conditions and environmental data in support of the ship trials results.

The USCG icebreaker MACKINAW served as the towing vehicle during the trials. Required towing capacity, towline apparatus and the MACKINAW'S powering characteristics were carefully assessed prior to testing. Considerable attention was paid to the logistics of towing one icebreaker with another. In fact, it was the high quality of seamanship which proved the key element in achieving the program goals.

Extensive instrumentation of MOBILE BAY was carried out in preparation for the trials. This included placement of thrust and torque systems on the propeller shafts to record self-propulsion data; and strain sensors on the towline to measure resistance data.

The details of the procedures utilized in the test program are described in the following sections. The trials data are fully presented and resistance equations postulated. On the basis of these results, full-scale trends for performance coefficients in level ice are derived. Subsequently thrust deduction, wake fraction and propulsive efficiency have been compared to available model test data.

In summary a small, but unique full-scale resistance database has been acquired for a typical icebreaking hull form series. This represents a long awaited milestone in the prediction of propulsive performance for ships in level ice.

1.2 Background

In the design of icebreakers, powering is determined by means of a prediction of propulsive performance. The two primary components of the performance equation are: the resistance of the hull as it moves through the water and ice, and the efficiency of the propulsion system which is selected to overcome this resistance. The preferred approach to defining realistic performance estimates for new designs would be based on full-scale resistance and self-propulsion data for a similar ship hull form and in the same ice conditions. However, full-scale towed resistance is not available. Self-propulsion trials data sets are more abundant; but they are closely associated with the propeller performance characteristics of the particular test ship and therefore not easily applied to new designs. This has led to the adaptation of clear-water model test methods as a cost effective means of estimating powering requirements.

Prediction of icebreaker resistance utilizes similar procedures to those which have evolved for ice free applications. The basic information is derived from model tests and experience from previous designs. For the case of open water model testing, more than 100 years of experience has resulted in techniques for estimating resistance with a high degree of confidence. Verification of model test techniques by towing full-scale vessels has played an important role from as early as 1874 and has included testing of the GREYHOUND, LUCY ASHTON, PENELOPE and ANTIOPE [1,2,3,4].

Corresponding full-scale research programs are needed to improve techniques in the ice basin. Each facility has evolved its own empirical procedures to correlate their model test data with observed full-scale data. However, there is poor agreement between approaches at different basins since both measured data and analysis techniques are directly determined by the characteristics of the ice material used. The ITTC ice committee has encouraged reform in this area by recommending standardized test procedures and by implementing an international program to compare results from R-Class and MV ARCTIC model tests at different ice basins. Nevertheless, a full-scale resistance reference line is a necessary starting point in evaluating the accuracy of different approaches and establishing a meaningful correlation.

Prior to the current program there has been only one serious attempt to measure full-scale towed ice resistance. The 120 (metric) tonne torpedo boat PERSEUS [8] was tested in sea ice near Stockholm, Sweden during 1967 and 1968. An empirical ice resistance formulation was derived which showed a velocity squared dependence and a linear variation with ice thickness. Practical difficulties in obtaining level ice conditions were reported which introduced considerable scatter into the results. Only limited data is presented. Furthermore the PERSEUS was not a typical icebreaker design; and therefore this experimental data has not played a significant role in the advancement of performance prediction methodology.

The parameters governing propeller performance behind a ship in ice are influenced both by the increased propeller loading and by interactions between the blades and ice fragments. The interaction may involve varying degrees of ice ingestion and blockage or ice milling. This causes several problems in replicating full-scale cusp failure at the bow and flow around the stern. In particular, the ice fragment size distribution in the broken channel differs for various model ice materials; and these in turn differ from trials observations. The availability of full-scale thrust data from trials provides assurance that the propulsion data is generally valid. However, the lack of corresponding full-scale resistance data has resulted in continued uncertainty about the expected values of thrust deduction.

The design effort for the 140 foot class of icebreakers included a broad spectrum of model tests and resulted in a very successful icebreaker. Its small size makes it suitable for towing by a larger icebreaker, such as the MACKINAW. The qualities made it an ideal candidate for full-scale towed resistance trials. The present towed trials of the MOBILE BAY followed on resistance and self-propulsion model tests carried out at CRREL [9, 10] and Arctec [11] on the 140-ft KATMAI BAY in 1979 [7]. Open water curves for the stock propeller 4665 and additional clear-water propulsion and bollard condition data were available from NSRDC tests [12]. Figure 1.2-1 shows MOBILE BAY and gives principal particulars. Figures 1.2-2 and 1.2-3 give the body plan and lines and open water propeller characteristics respectively.

1.3 Test Program Objectives

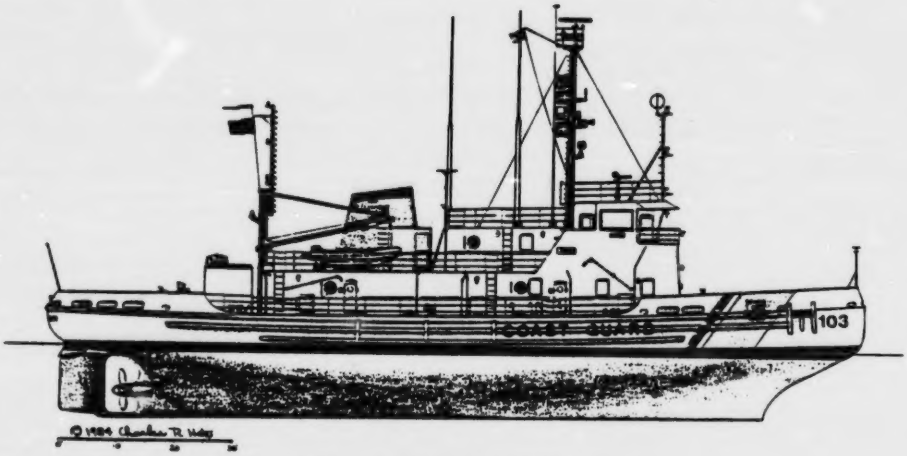
The trials of MOBILE BAY were intended to answer a myriad of questions related to the prediction of icebreaker performance. These objectives may be stated as a combination of general data collection objectives and specific analysis objectives:

- Collect full-scale towed resistance of the WTGB MOBILE BAY in ice to allow:
  - verification of alternative forms of empirical resistance equations,
  - evaluation of model test resistance estimates which are derived from basin test programs using various modelling materials and scale factors,
  - derivation of propulsion parameters from self-propelled tests at full-scale in the same ice field.

- Collect data on full-scale self-propelled performance of the WTGB MOBILE BAY in ice to allow:
  - expansion of the data base started by VANCE [7],
  - derivation of propulsion parameters using full-scale towed resistance data to assess effects of ice,
  - evaluation of propulsion parameter estimates derived from self-propelled model tests,
  - assessment of the influence of propeller-ice interactions.

These objectives have been addressed throughout the planning, testing, data reduction, and analysis phases of this work. It has not been possible to ascribe definitive conclusions for all of these questions since the range of many test parameters such as ice thickness and flexural strength have been limited by the environmental conditions encountered during the trials period. This limitation has not detracted from the overall success of this program.

LOA	140 ft. (42.68 m)
LWL	130 ft. (39.63 m)
B_{max}	37 ft. 6 in. (11.43 m)
B_{wl}	34 ft. 2 in. (10.41 m)
DRAFT	12 ft. (3.66 m)
# PROPELLERS	1
SHP	2500 SHP (1864 KW)
PROPULSION TYPE	DE



USCGC MOBILE BAY (WTGB-103)

Figure 1.2-1

PRINCIPAL PARTICULARS OF MOBILE BAY

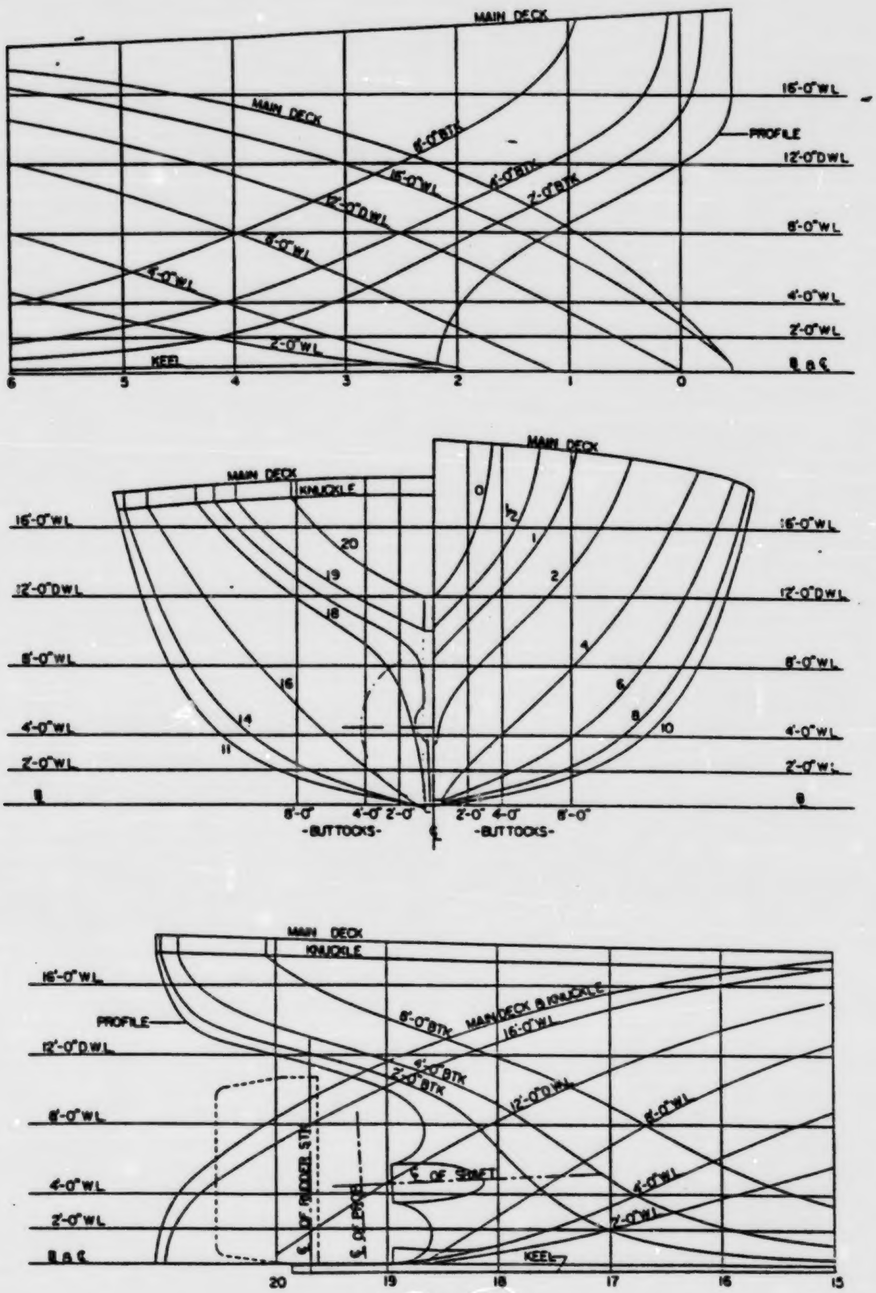
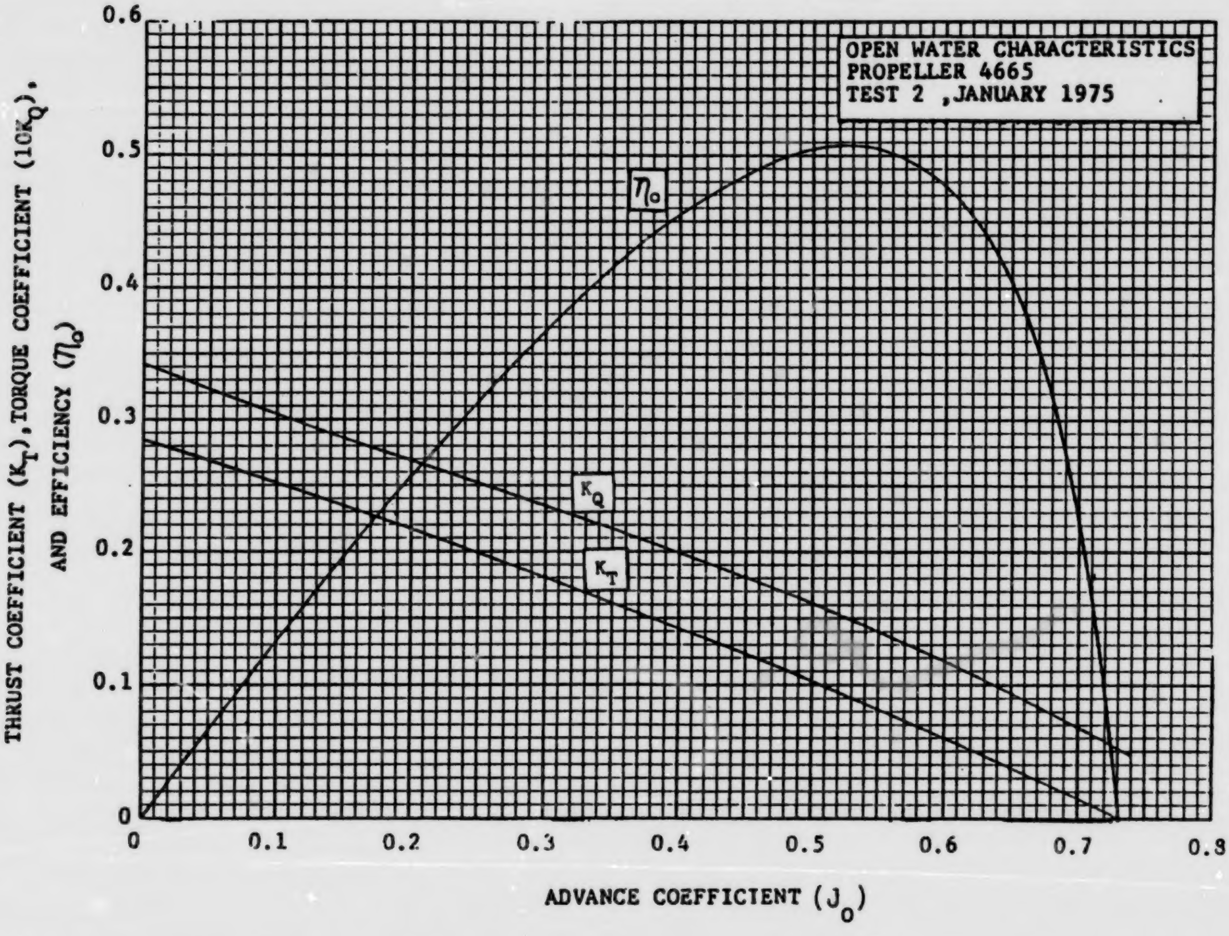

MAIN DECK
16'-0"WL
PROFILE
12'-0"DWL
8'-0"WL
4'-0"WL
2'-0"WL
℄ & ℄
MAIN DECK
8'-0"BTK
16'-0"WL
4'-0"BTK
12'-0"DWL
2'-0"BTK
8'-0"WL
4'-0"WL
2'-0"WL
KEEL
6
5
4
3
2
1
0
MAIN DECK
KNUCKLE
MAIN DECK
16'-0"WL
12'-0"DWL
8'-0"WL
4'-0"WL
2'-0"WL
℄
0
½
1
2
4
6
8
10
20
19
18
16
14
11
8'-0"
4'-0"
2'-0"
-BUTTOCKS-
℄
2'-0"
4'-0"
8'-0"
-BUTTOCKS-
MAIN DECK
KNUCKLE
16'-0"WL
PROFILE
12'-0"DWL
8'-0"WL
4'-0"WL
2'-0"WL
℄ & ℄
8'-0"BTK
MAIN DECK & KNUCKLE
16'-0"WL
4'-0"BTK
2'-0"BTK
12'-0"DWL
8'-0"WL
℄ OF SHAFT
℄ OF RUDDER STK
℄ OF PROP
4'-0"WL
2'-0"WL
KEEL
20
19
18
17
16
15

FIGURE 1.2-2

ABBREVIATED LINES AND BODY PLAN
OF UNITED STATES COAST GUARD 140-FOOT WYTM [ref.12]



Stock No.: 4665
Diameter: 8.50 ft (2.59 m)
Pitch: 6.18 ft (1.88 m)
No. of Blades: 4
Direction of Rotation: RH

FIGURE 1.2-3

OPEN-WATER PROPELLER CHARACTERISTICS [ref.12]

2. TEST SETUP AND OPERATIONS

During the planning phase of this program the proposed ship towing procedures were carefully reviewed to optimize the data collection and to ensure safe operating conditions. Three critical areas of concern were addressed:

- Was the MACKINAW's propulsive capacity sufficient to tow the MOBILE BAY at the maximum test speeds in the expected ice conditions? Did the predicted towing loads in these conditions exceed the elastic yield strength of the tow cable or intrude within a safety margin?
- Could practical maneuvers be defined to pull the MOBILE BAY behind the MACKINAW with 600m (2000 ft) of towline such that the MOBILE BAY would see unbroken level ice?
- Would the instrumentation system adequately support all the required data acquisition and ship monitoring functions, including: performance data for MOBILE BAY, towline tension, and displays aboard MACKINAW for guidance and safety?

After assessing the resistance characteristics of MOBILE BAY and comparing this to performance curves for MACKINAW, it was concluded that MACKINAW has more than adequate towing power in all test conditions. The calculations showed that MACKINAW was capable of overcoming not only her own resistance in open water and ice, but also the predicted maximum drag of MOBILE BAY.

The estimation of maximum towline pull was based on ice resistance data from ARCTEC and CRREL model tests for the 140 ft WTGB hull form and a review of self-propulsion results from the full-scale KATMAI BAY trials. This maximum pull was within the safe working strength of the standard 50mm (2 in) steel cable aboard MACKINAW, assuming a safety factor of 4 to account for dynamic peaks and other uncertainties. The load sensing clevis pin has a total capacity of 800MN (180,000 lb) and therefore was acceptable for measuring tension in the towline. Details of the assessment procedures are given in the test plan, [18].

The project team encouraged active participation by experienced Coast Guard personnel in drawing up the towing plans. The cooperation and quality of seamanship of the officers and crew of MACKINAW and MOBILE BAY was also a crucial factor in the successful implementation of the maneuvering procedures and operation of towing equipment. The result was a towing scheme whereby the MACKINAW maneuvered in a broad loop around a test area and then straightened out to commence towing of MOBILE BAY across this test area.

Concerns about the feasibility of the instrumentation system to fulfill a multiplicity of tasks and other facets of the test plan are described in the following sections.

2.1 Test Instrumentation

The test instrumentation used during this program falls into three basic groups:

- Ship performance and towline tension measurement and data collection onboard MOBILE BAY;
- Advisory display using telemetry link of towline tension and MOBILE BAY thrust and speed on both ships;
- Load and deflection of in-situ cantilever beams to determine ice strength.

The first two groups are described below, while the third is properly included within the later discussion of ice strength measurements.

Figure 2.1.1 illustrates the general organization of the instrumentation system for measurement, processing, storing, and displaying the ship performance parameters during a test. Each of these functions are discussed separately in the following sections.

2.1.1 Measurement of Test Parameters

Operating procedure during towed tests required a nominal propeller thrust to offset the propeller appendage drag, and therefore five separate parameters are measured in both resistance and self-propulsion tests of the MOBILE BAY:

- Shaft thrust
- Shaft torque
- Shaft RPM
- Ship speed
- Towline tension

Each of these measurements required unique measurement and signal conditioning equipment. Details of the systems used are given in Appendix A and are summarized in Table 2.1.1. The following outline of the implemented system describes its salient features:

SHAFT THRUST: Shaft thrust was obtained by placing strain gages on the shaft just forward of the stern tube seal to measure compression of the shaft, an indication of thrust. An FM telemetry unit with a loop antenna was attached to the shaft to pass strain signals from the shaft to a pickup unit. Voltage for bridge excitation was provided by battery packs on the shaft and regulated by the transmitter circuitry. The gages were a wieldable type with integral leads. Very precise alignment was achieved, resulting in no measurable coupling between thrust and torsion signals.

SHAFT TORQUE: Torque in the tailshaft was measured at the same location as thrust. Identical equipment was used, with the exception of the modified strain gage bridge arrangement to measure torsional stress.

SHAFT RPM: Shaft RPM was recorded from the existing output of the tachometer/generator installed as part of the propulsion monitoring/control system. The output of this device over the range of interest was ±60v, so the signal was attenuated using a Honeywell 117 attenuator/amplifier.

SHIP SPEED: MOBILE BAY's speed of advance was measured using a doppler radar. The radar gun was mounted on the starboard rail about 12m (40 ft) aft of the bow and aimed aft at the ice alongside the ship. The radar was calibrated using tuning forks provided for that purpose.

TOWLINE TENSION: Towline tension was measured at the bow of MOBILE BAY using a strain gaged clevis pin sensitive in shear. The pin, described in Appendix A, was manufactured by Strainsert. Calibrations performed prior to the deployment were verified by shunt resistor techniques on site.

With the exception of protective measures required for the clevis pin and discussed in later sections, these instruments performed without trouble for the entire test program. Signals from these sensors were filtered and amplified or attenuated as required using Honeywell and Vishay instrumentation conditioners to provide outputs for the data collection and monitoring systems with ± 5v full scale. These systems are described in the following sections.

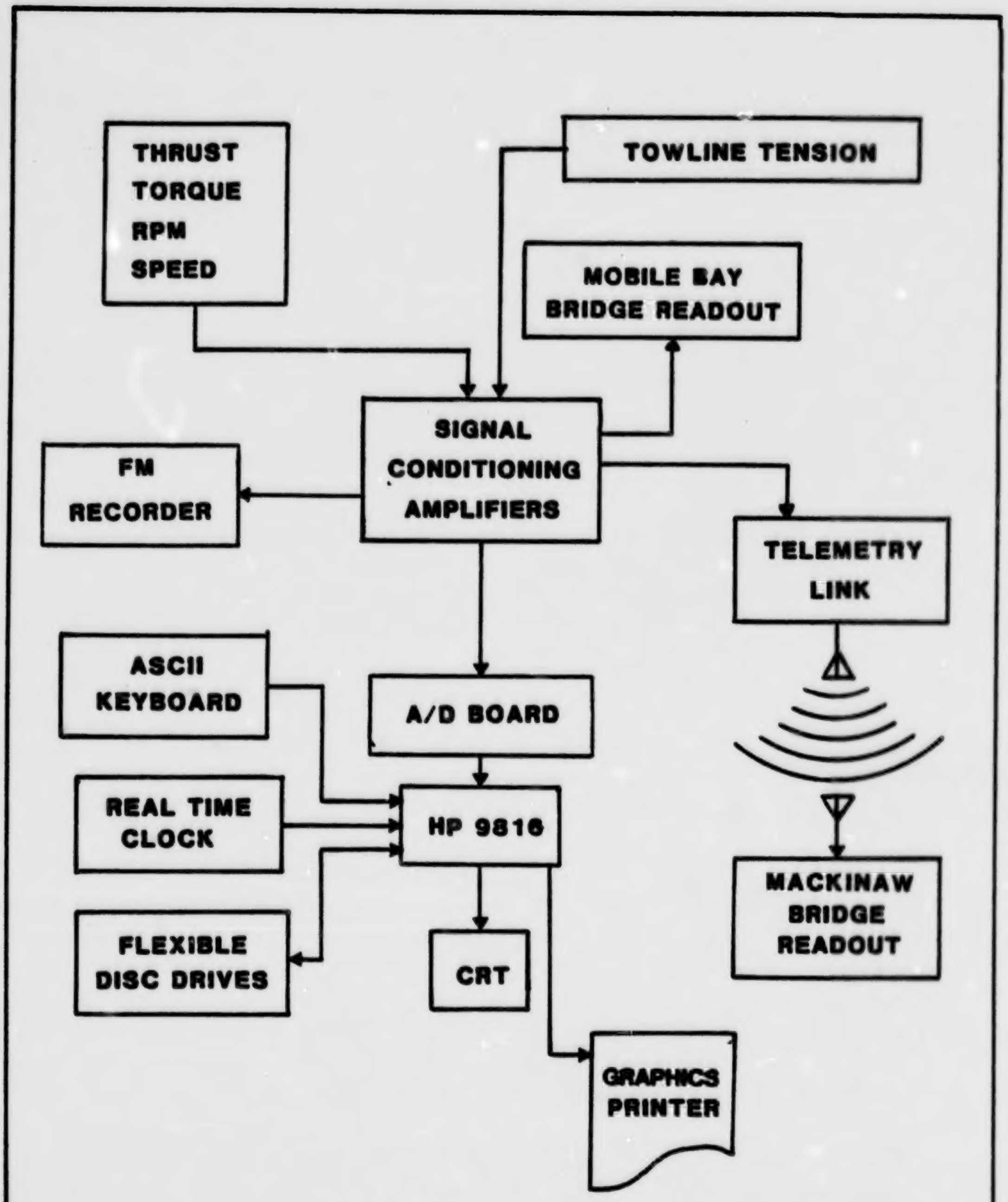

THRUST
TORQUE
RPM
SPEED
TOWLINE TENSION
MOBILE BAY BRIDGE READOUT
SIGNAL CONDITIONING AMPLIFIERS
FM RECORDER
TELEMETRY LINK
ASCII KEYBOARD
A/D BOARD
REAL TIME CLOCK
HP 9816
MACKINAW BRIDGE READOUT
FLEXIBLE DISC DRIVES
CRT
GRAPHICS PRINTER

Figure 2.1-1

BLOCK DIAGRAM OF INSTRUMENTATION AND DATA ACQUISITION HARDWARE

TABLE 2.1-1

TEST SENSOR SUMMARY

PARAMETER	SENSOR TYPE	CALIBRATION METHOD	CALIBRATION RANGE
Shaft Thrust	In-situ Strain Gages	Resistance Shunt	-356,000 to +356,000 N
Shaft Torque	In-situ Strain Gages	Resistance Shunt	-74,600 to +74,600 N.M
Shaft RPM	Ship's Tach/generator	Optional Strobe	-300 to +300 RPM
Ship Speed	Dopplar Radar	Tuning Forks	0 - 10 knots
Towline Tension	Straingaged Clevis Pin	Resistance Shunt	0 - 778 MN

NOTE: All sensor outputs are attenuated or amplified to provide ± 5v as input to the data acquisition system. All channels filtered at 1Hz and sampled @ 4Hz.

2.1.2 Data Collection and Processing

Data collection for these tests was accomplished with a system based on a Hewlett Packard 9816 computer. The systems feature 1 megabyte of RAM, twin disk drives for storage, an internal A/D processor board for actual data interface, and a graphics printer for output of both text and graphics.

Data acquisition software was configured to collect real time digital data on all five channels at 4Hz. Internal memory capacity allowed tests of up to 10 minutes duration. Separate programs were available for sensor calibration and signal verification. The data acquisition program allowed for active monitoring of data both before and during the test interval. Within 5 minutes after the test, statistical analysis and graphic results were available, similar to that shown in Plate 2-1.

This equipment, along with the signal processing equipment and monitor disply, were mounted on the chart table on MOBILE BAY's bridge, as shown in Figure 2.1-2.

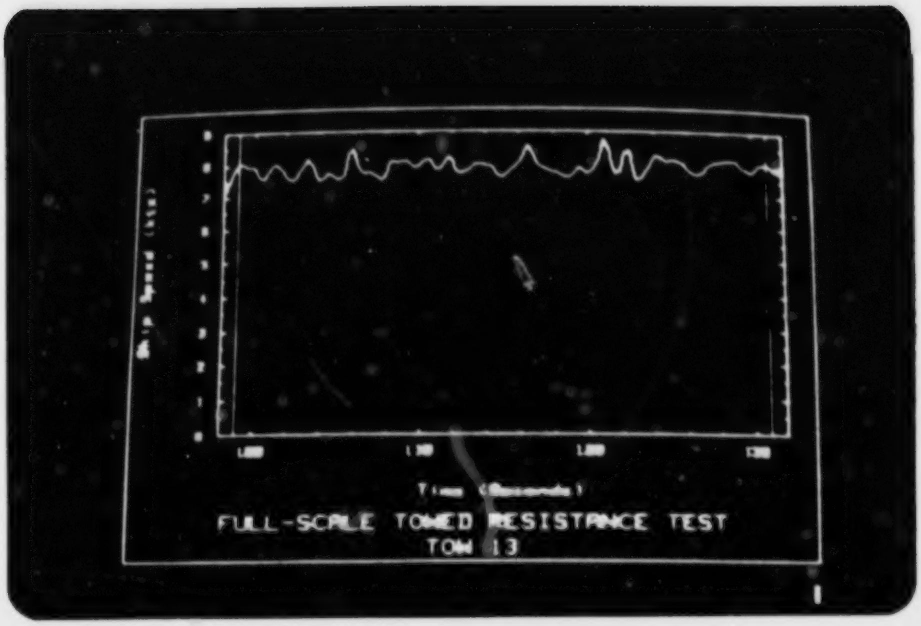


PLATE 2-1 TYPICAL GRAPHIC DISPLAY FROM ONBOARD DATA ACQUISITION SYSTEM

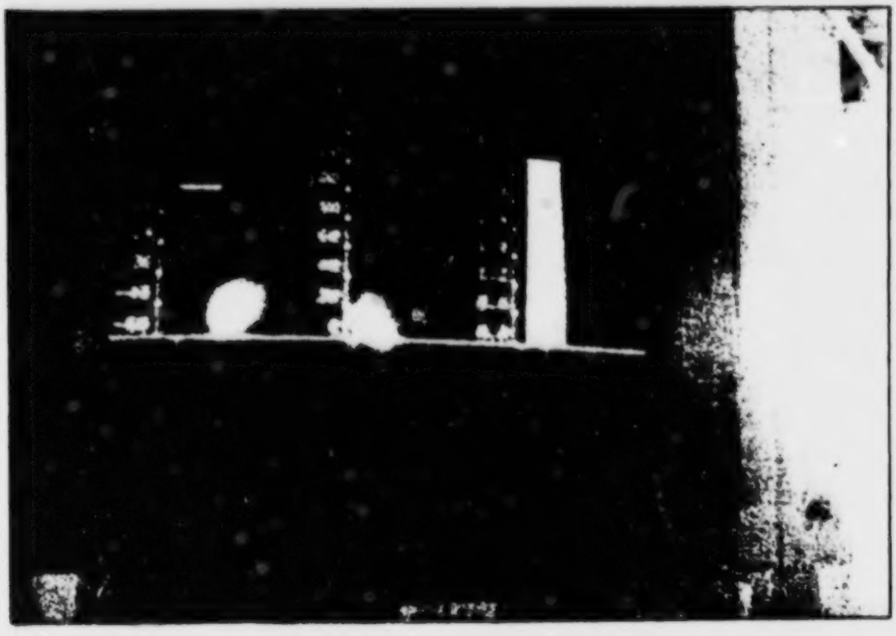


PLATE 2-2 TYPICAL DISPLAY ON MACKINAW MONITOR

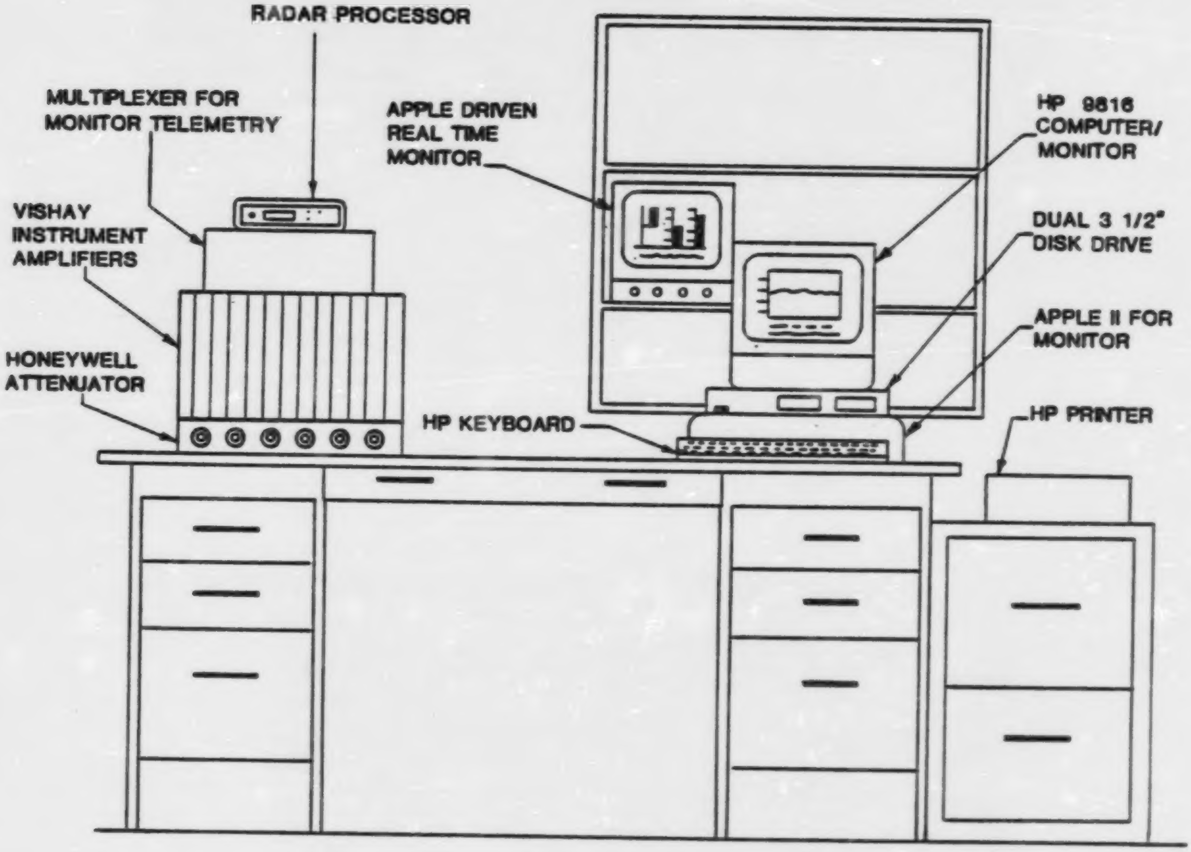

RADAR PROCESSOR
MULTIPLEXER FOR MONITOR TELEMETRY
VISHAY INSTRUMENT AMPLIFIERS
HONEYWELL ATTENUATOR
APPLE DRIVEN REAL TIME MONITOR
HP KEYBOARD
HP 9816 COMPUTER/ MONITOR
DUAL 3 1/2" DISK DRIVE
APPLE II FOR MONITOR
HP PRINTER

Figure 2.1-2

ARRANGEMENT OF SIGNAL PROCESSING EQUIPMENT ON BRIDGE OF MOBILE BAY

2.1.3 Bridge Display Monitors

In order to coordinate testing and provide information for safe towing operation it was decided that a monitoring system for use on the bridge or MACKINAW was desirable. This sytem was to report towline loads, velocity, and MOBILE BAY thrust. Since all parameters were measured on MOBILE BAY, either a cable or telemetry link to MACKINAW was required. Telemetry was chosen to reduce the cost and logistic problems associated with a cable system.

Figure 2.1-3 shows the monitor system as implemented. APPLE IIe computers with internal A/D processors were used to read and display the data. The analog data was fed directly to the system on board MOBILE BAY and multiplexed for transmission to MACKINAW. The display is illustrated in Plate 2-2, it was calibrated a number of times during the test program and proved highly valuable for monitoring the steady state velocity and dynamic tensions in the cable.

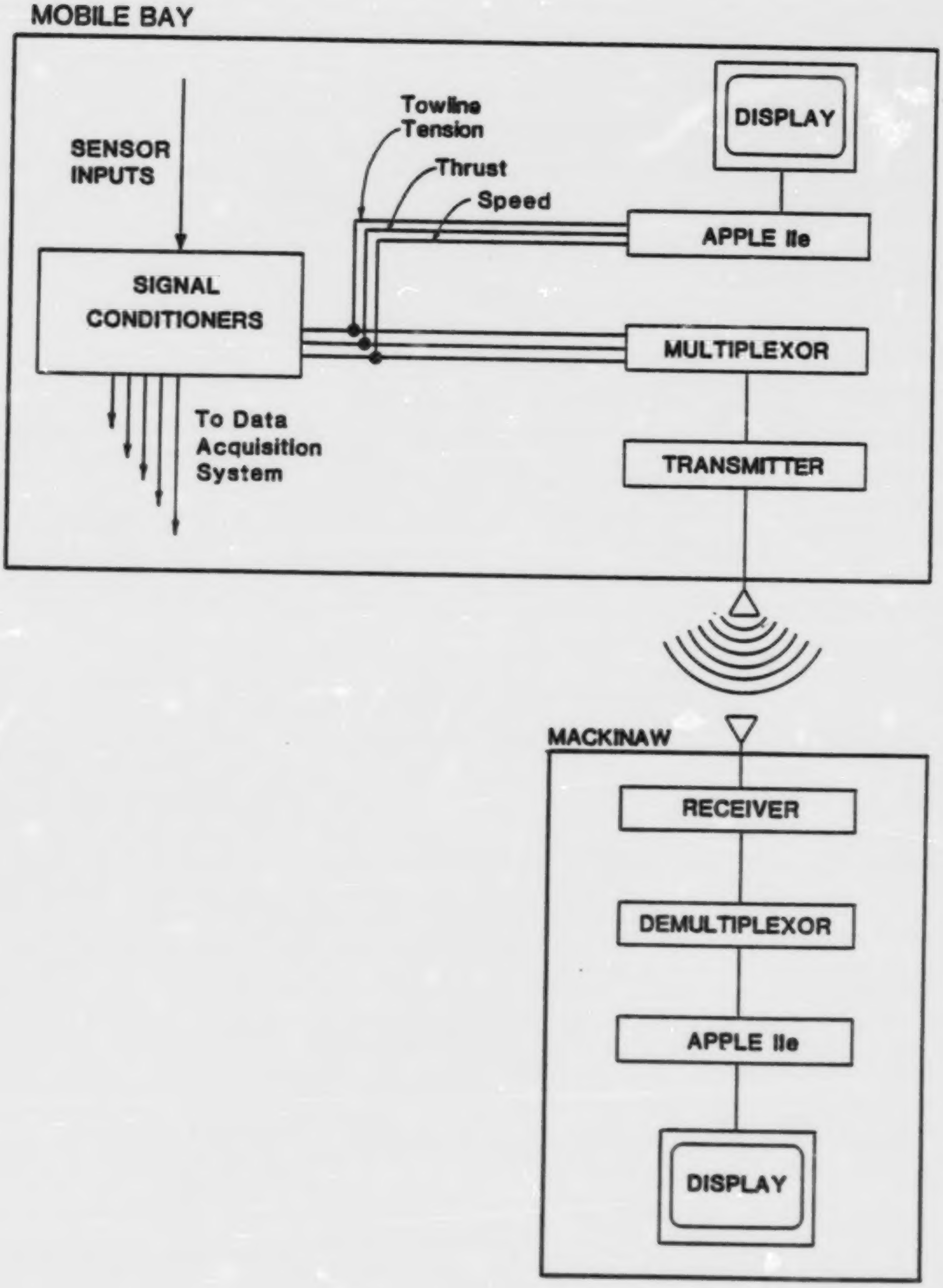

MOBILE BAY
SENSOR INPUTS
Towline Tension
Thrust
Speed
DISPLAY
APPLE IIe
SIGNAL CONDITIONERS
MULTIPLEXOR
To Data Acquisition System
TRANSMITTER
MACKINAW
RECEIVER
DEMULTIPLEXOR
APPLE IIe
DISPLAY

Figure 2.1-3

ARRANGEMENT OF MONITOR EQUIPMENT ON MACKINAW AND MOBILE BAY

2.2 Self-Propelled Test Procedures

Approximately 12 hours of testing during the program was dedicated to collecting self-propelled data. The first four hour period was during transit from Rock Island in northern Green Bay to Escanaba on the evening of the 21st of February. The data collected was primarily to prove out procedures, and problems with ice thickness measurements has limited its utility.

Data collection on the 23rd and 24th was carried out successfully. The procedure, as outlined below, was similar on both days.

> PRIOR TO TESTING: A review of visual and radar observations made during previous tests was used to identify a sufficiently large area of smooth level ice for testing. MOBILE BAY then transited to the edge of the area chosen. A planned pattern, similar to that shown in Figure 2.2-1 was formulated with Captain Dejung and target power settings selected.
>
> TESTING: Runs down each leg of the planned course were carried out, varying power levels to obtain discrete data points over each portion. During the turn to come around to the next leg, the data was stored and a new test sequence initiated. The ship was brought to all stop after the turn, and new zero's recorded and target power settings verified. The next leg was then run and this process was repeated.
>
> AFTER TEST RUNS: At the end of the testing a team was sent onto the ice to document ice conditions in the ship's track. Figure 2.2-2 shows a tracing from radar of the track using the plan of Figure 2.2-1 as a guide.

The test plan illustrated in Figure 2.2-1, or 2.2-2 provided for an assessment of the influence of pressure relief. Because of the concern that pressure relief could introduce distortion into the propulsive coefficient trends, the test plan called for similar tracks in both towed resistance and self-propulsion trials. Data sampling was stopped at the first sign of crack formations involving the previous track. Tests SP11, SP12, and SP13 were in level unbroken ice without a parallel broken channel which could reduce confinement pressures on MOBILE BAY. In tests SP14, SP15, SP16 and SP17 the previous broken channel was parallel to the track. It was therefore possible to compare thrust data from the two cases as an indicator of the magnitude of the pressure relief effect on the measured resistance.

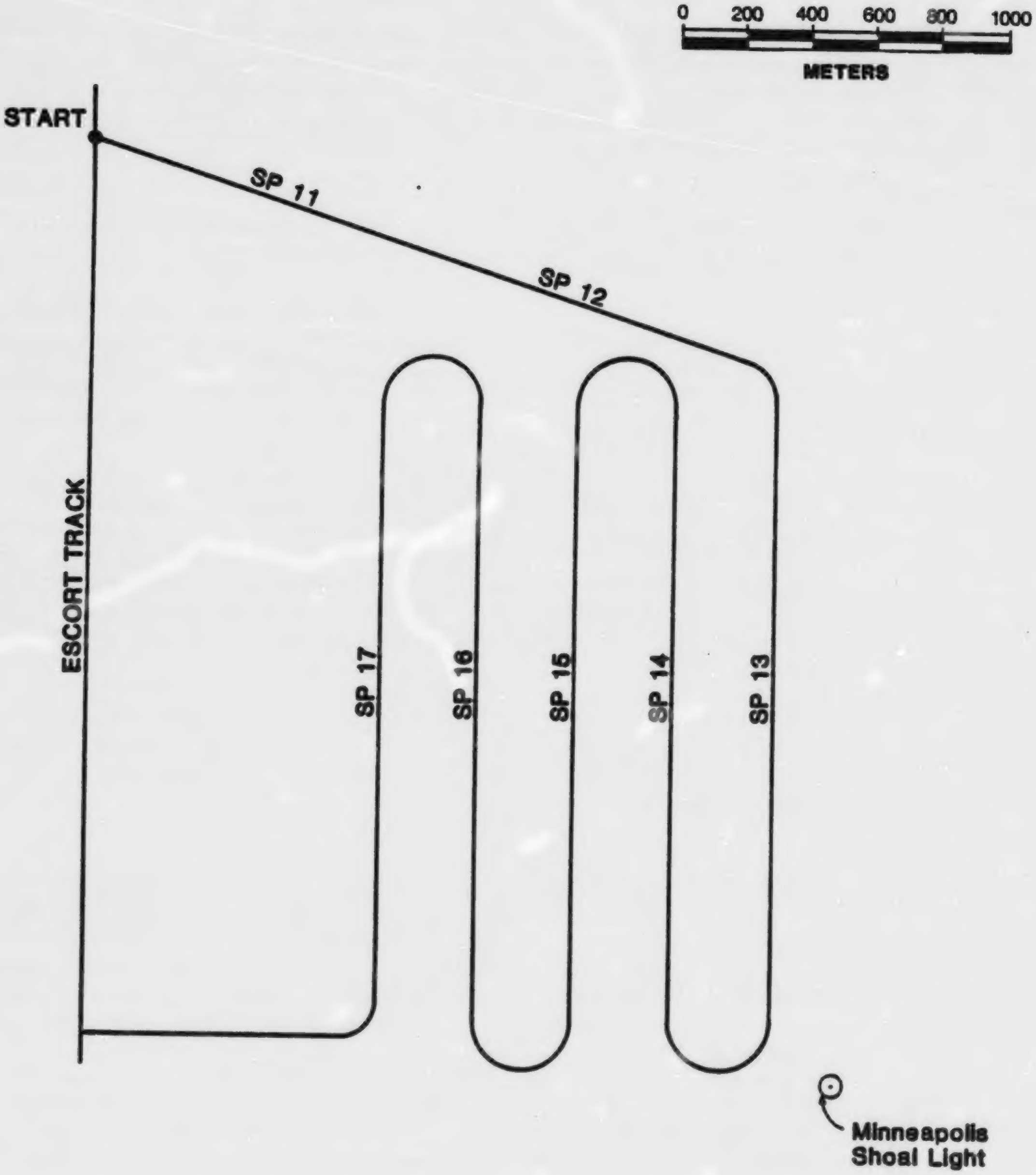

0
200
400
600
800
1000
METERS
START
SP 11
SP 12
ESCORT TRACK
SP 17
SP 16
SP 15
SP 14
SP 13
Minneapolis Shoal Light

Figure 2.2-1

PLAN FOR SELF PROPELLED TESTS ON 2/24/86

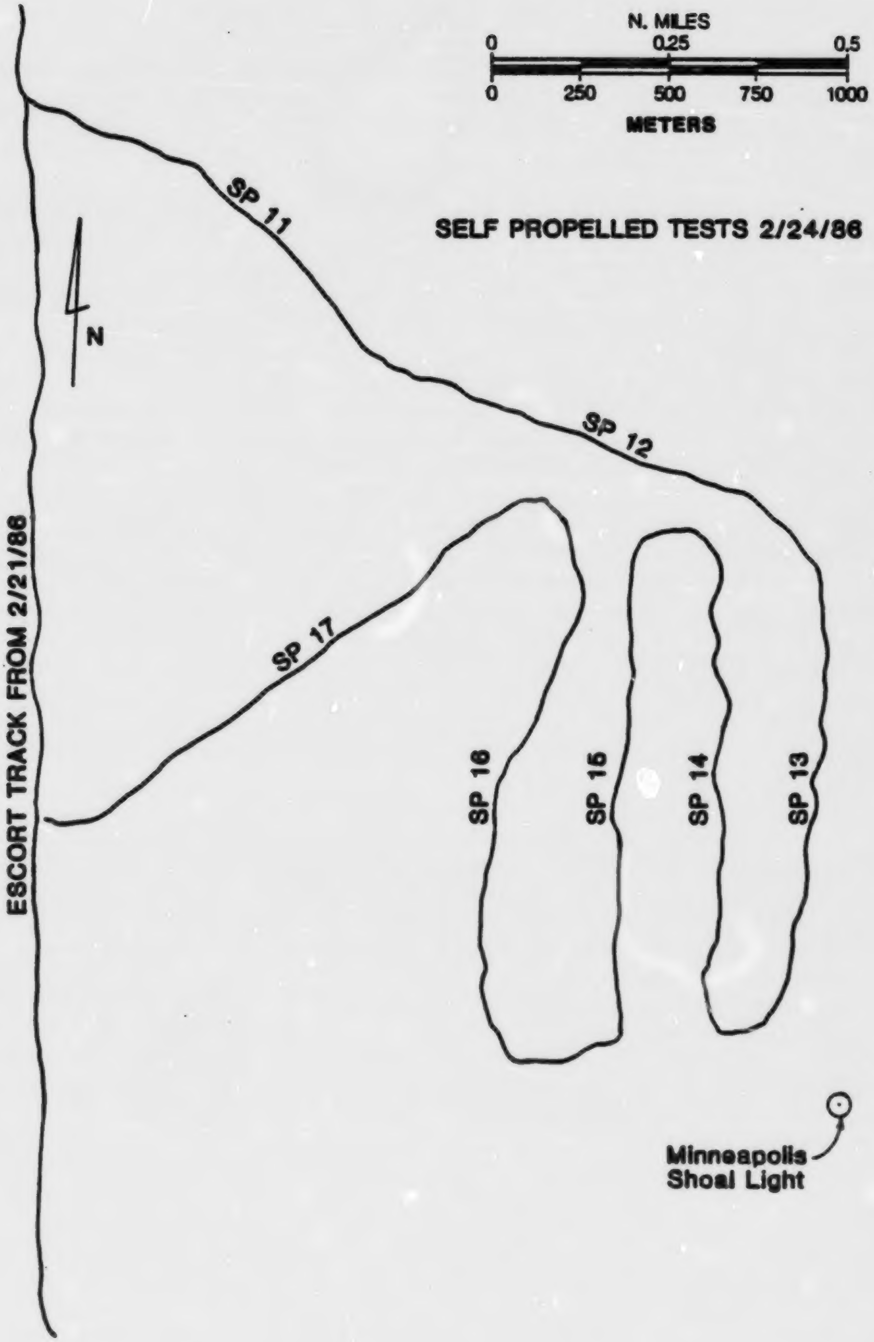

N. MILES
0
0.25
0.5
0
250
500
750
1000
METERS
SELF PROPELLED TESTS 2/24/86
SP 11
N
SP 12
SP 17
ESCORT TRACK FROM 2/21/86
SP 16
SP 15
SP 14
SP 13
Minneapolis Shoal Light

Figure 2.2–2

ACTUAL TEST TRACKS OBSERVED ON RADAR FOR 2/24/86

2.3 Towed Test Procedures

The successful completion of the towed resistance tests was made possible by the cooperation and innovation of the commanding officers and crews of MACKINAW and MOBILE BAY. Extensive work was required to develop mechanical arrangements and procedures to make these tests a success.

The first roadblock was the development of towing hardware and arrangements. Figure 2.3-1 and Plate 2-3 and 2-4, show the equipment used which was a combination of existing hardware and application specific items. The two 3.3cm bridle legs were 10.7m (35 ft) long and constructed specifically for this task. Existing bridles proved too long to control the fishplate and strain sensor. The bridles were attached to kingpins on the aft end of the foredeck, which were the only existing points rated to carry the expected load. The outer ends of the bridles were joined to a custom made fishplate, shown in Plate 2-4. This was modelled after a similar plate on board MACKINAW, and designed to accommodate the load sensing pin. A 12cm nylon mooring line was attached to the fishplate to take up load as the tow cable went slack. It was intended to keep the plate and pin out of the ice and out from under the forefoot. This preventer system was implemented after ice had damaged the signal cable and connectors on the pin at an early stage in the test program. The heavy preventer and an armoured cap on the pin were developed by the ships' crews to prevent further problems. Plate 2-5 shows ice climbing the cable during retrieval, demonstrating the need for these measures. The load from the steel tow hawser was transferred to the pin via a 1.5m (5') pennant, which had a poured shackle on one end (Plate 2-4) to facilitate its attachment to the tow cable.

Two options were considered for getting the ships into position for the tests: maneuvering the ships independently and dragging the cable across the ice or maneuvering the ships with cable connected. The first approach was considered impractical with the available equipment and was not attempted. That the second approach was successful is a testament to the skill and creativity of both commanding officers. The following description of these procedures was taken from notes prepared by LT John Dejung, commanding officer of the MOBILE BAY. The references in parenthesis, (), refer to plates showing various stages of the operation. S.I. units have been inserted into the text of the description.

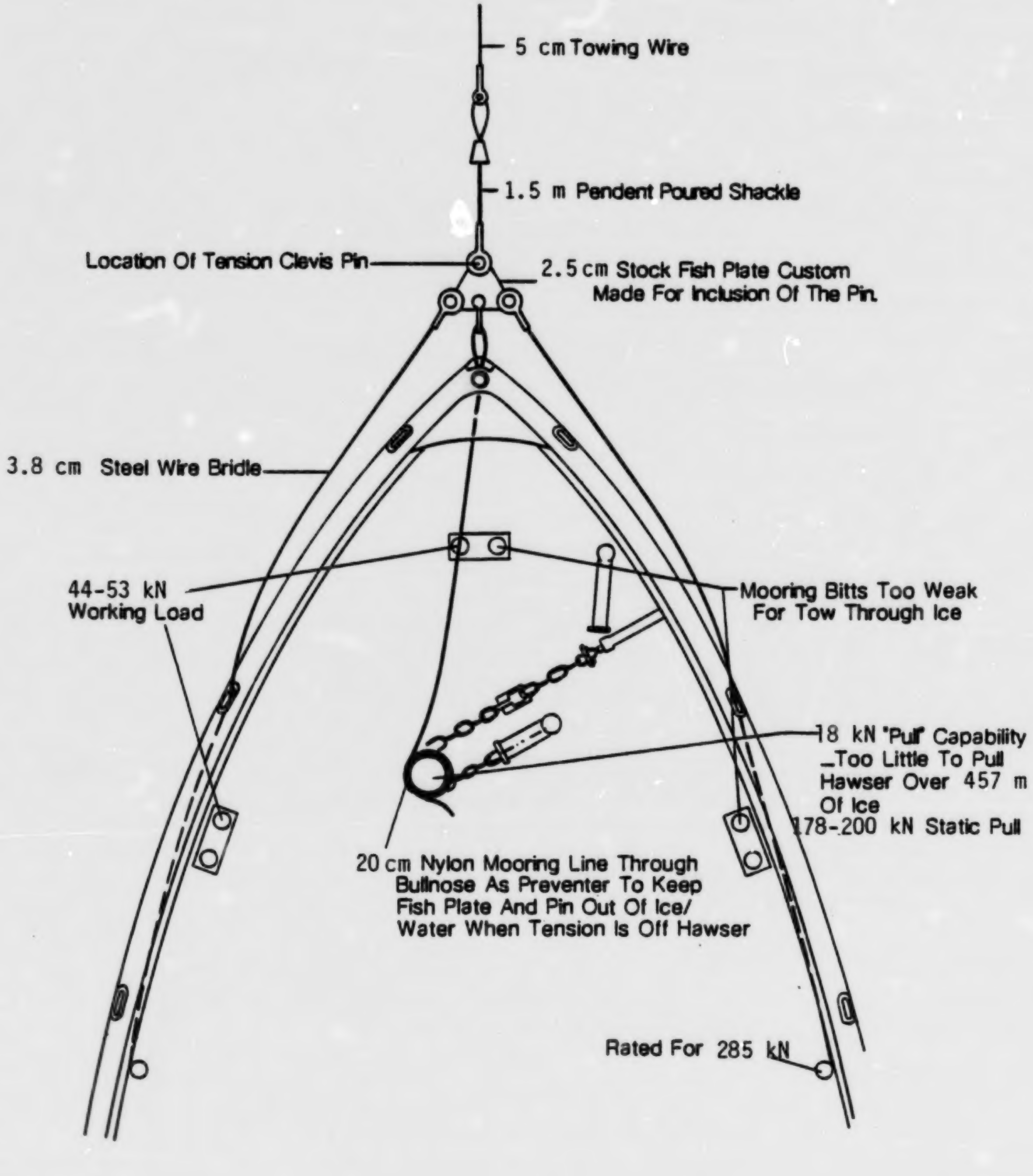
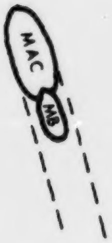

5 cm Towing Wire
1.5 m Pendent Poured Shackle
Location Of Tension Clevis Pin
2.5 cm Stock Fish Plate Custom Made For Inclusion Of The Pin.
3.8 cm Steel Wire Bridle
44-53 kN Working Load
Mooring Bitts Too Weak For Tow Through Ice
18 kN "Pull" Capability _Too Little To Pull Hawser Over 457 m Of Ice
178-200 kN Static Pull
20 cm Nylon Mooring Line Through Bullnose As Preventer To Keep Fish Plate And Pin Out Of Ice/ Water When Tension Is Off Hawser
Rated For 285 kN

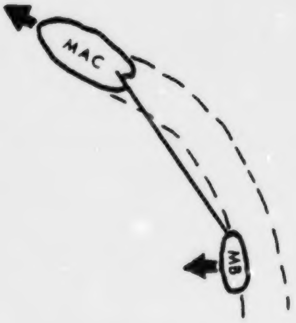
Figure 2.3-1

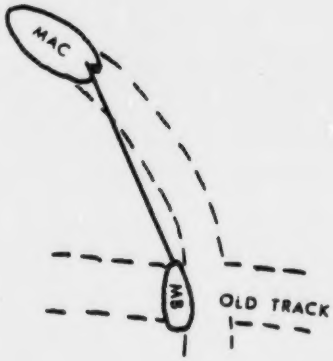
FOREDECK ARRANGEMENT

Operations started with MOBILE BAY secured in MACKINAW's stern notch, (Plate 2-6), or close aboard. With MOBILE BAY in the notch before each series of tests the bridle/tow cable assembly was rigged on MACKINAW's afterdeck.

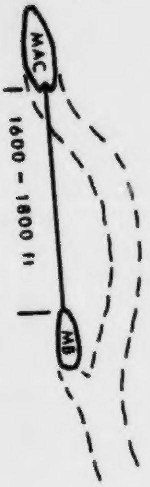


As the ships move apart, MACKINAW steaming ahead while MOBILE BAY backed, enough tension was kept on the tow cable to keep it out of the water, (Plates 2-7 and 2-8). MOBILE BAY's backing bells and a left turn by MACKINAW easily accomplished the task of bringing the cable over the top of the unbroken ice on the port side of the track, (Plates 2-9 and 2-10). The side force and wash generated by MOBILE BAY's backing bells weakened the ice on the port side and allowed MOBILE BAY to 'eat' into the ice sideways, (Plate 2-11). This was often enhanced by either MACKINAW or MOBILE BAY starting a notch on the side of the track or utilizing an existing crossing trackline.

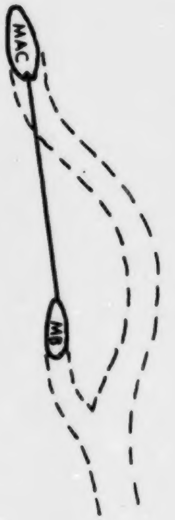




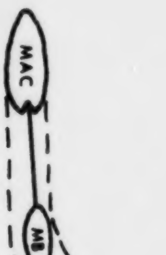
Once on the ice the hawser was payed out as MACKINAW continued forward and MOBILE BAY held position using backing bells, (Plate 2-12). As 1500' [457m] of cable was reached, MACKINAW would swing back to starboard to get a better directional line for the test. MACKINAW and MOBILE BAY then hove to with both firmly in the ice and 1600'-1800' [488-549m] of cable deployed. (Plate 2-13 shows the ship tracks for a typical test as it appeared at this point in the procedure.) The critical goal during this evolution was to ensure adequate ice between the expected tow track and MACKINAW's broken track.



Once in position the ARCTEC test team would deploy from MACKINAW and measure the ice thickness along the expected track and lay out flags for speed checks, (Plates 2-14 and 2-15). After the survey team reboarded MACKINAW the test was conducted, (Plate 2-16). As MACKINAW towed the MOBILE BAY ahead, MOBILE BAY used ahead bells to reduce acceleration loads and distance. The propulsion revolutions were adjusted to provide zero thrust level as test speed was approached. Data collection continued till relief cracks, (Plate 2-17), appeared ahead or to starboard of MOBILE BAY. (Plate 2-18 shows the completed test shown previously as it appears on radar. Figure 2.3-2 shows the tracing taken of this test, and Appendix C contains tracings of ship tracks for a majority of the tow tests.)



After the test, MACKINAW would slow to a stop and MOBILE BAY would "back like crazy " to keep the weight of the tow line, (now in the broken track), from jerking the 140 ahead and overrunning the towing bridle. MOBILE BAY kept backing bells on to keep tension as MACKINAW's winch retrived the cable, bringing MOBILE BAY to the notch or a short stay and ready for the next test.



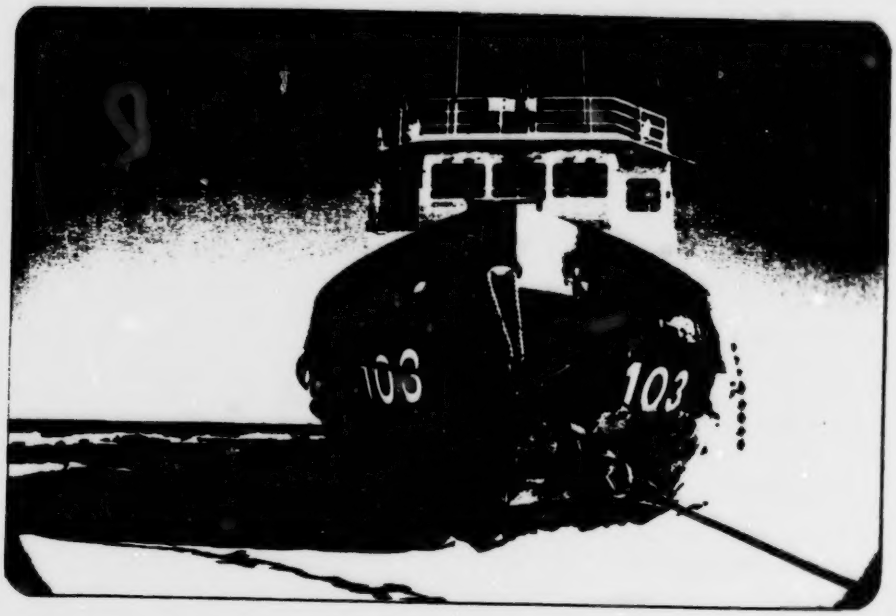


PLATE 2-3 BOW VIEW OF MOBILE BAY SHOWING TOWING ARRANGEMENT

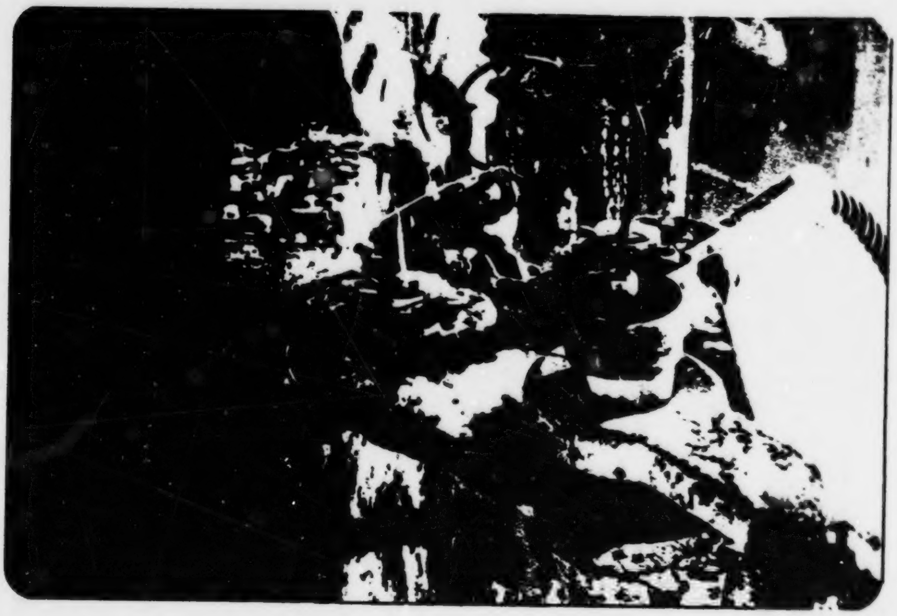


PLATE 2-4 CLOSE-UP OF FISH-PLATE SHOWING LOAD SENSOR INSTALLATION

PLATE 2-5 THIS VIEW SHOWS HOW ICE THREATENED THE PIN DURING RETRIEVAL. NOTE TENSION ON THE NYLON PREVENTER.

PLATE 2-6 ARRANGEMENT PRIOR TO TEST WITH MOBILE BAY IN MACKINAW'S NOTCH

PLATE 2-7 MOBILE BAY BACKING DOWN PRIOR TO TEST AFTER MAKING UP TOW

PLATE 2-8 LINE PAYOUT AS MOBILE BAY BACKS AND MACKINAW MOVES AHEAD

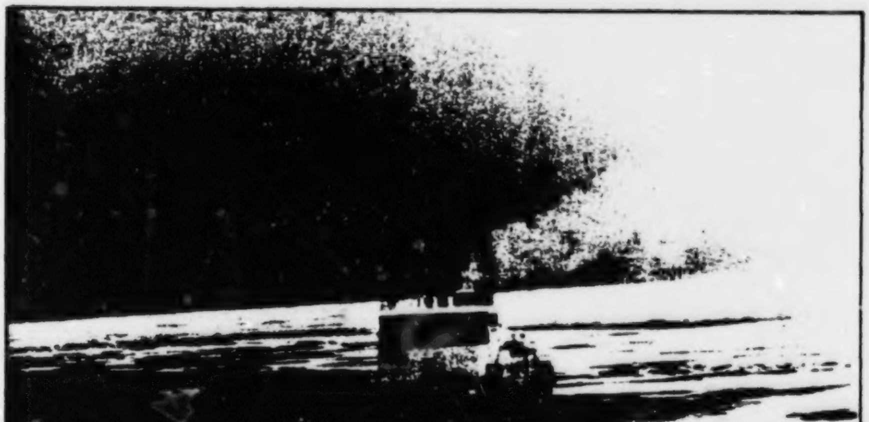


PLATE 2-9 MOBILE BAY IN POSITION ABEAM OF NOTCH IN THE SIDE OF THE TRACK

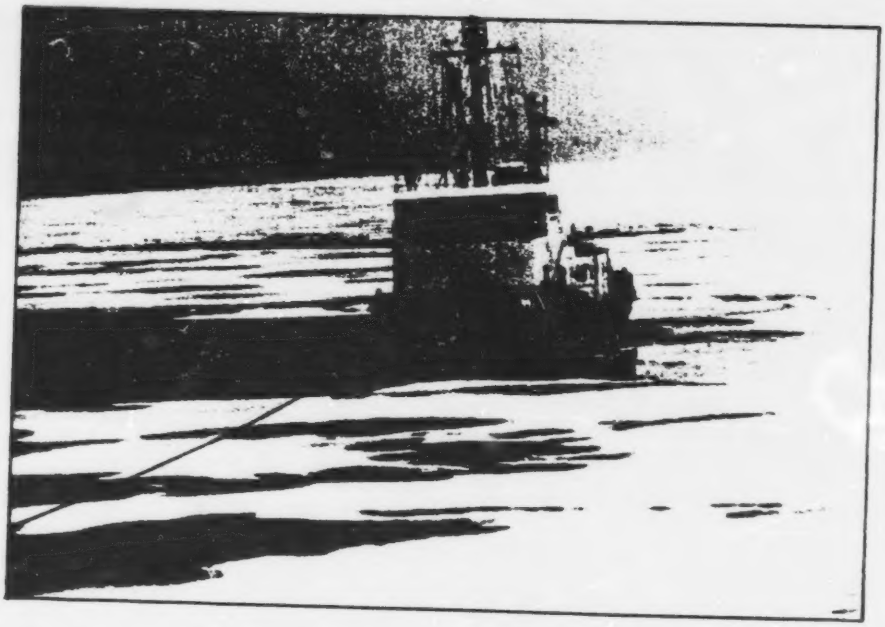


PLATE 2-10 MOBILE BAY WORKING TO PORT AS MACKINAW MOVES FORWARD

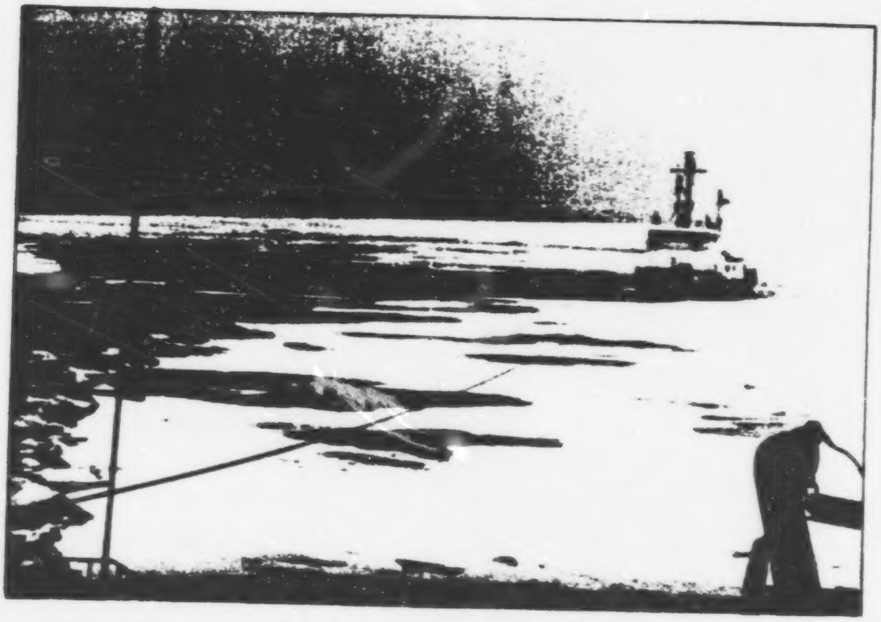


PLATE 2-11 AS CABLE IS PAYED OUT IT FALLS TO THE ICE TO PORT OF MACKINAW'S TRACK

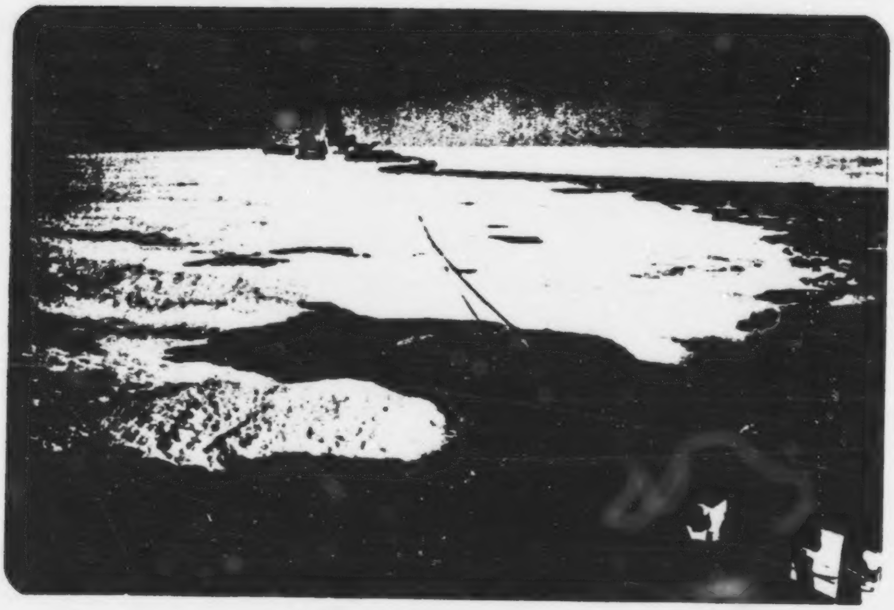


PLATE 2-12 MACKINAW CONTINUES TO DEPLOY CABLE AS SHE MOVES AHEAD

PLATE 2-13 VIEW OF TRACKS BEFORE TEST AFTER CABLE IS FULLY DEPLOYED

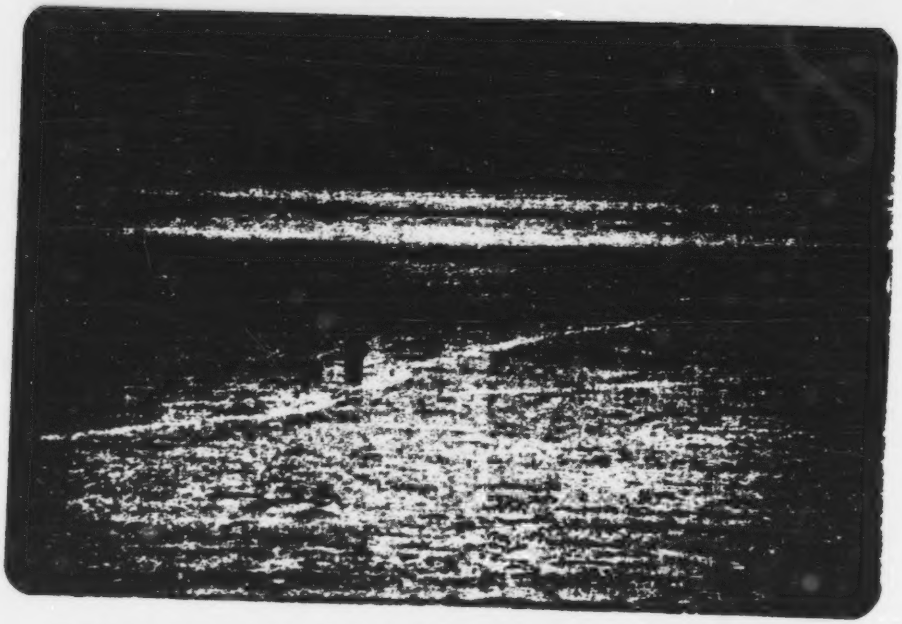


PLATE 2-14 PRIOR TO TOW ON-ICE MEASUREMENTS OF THICKNESS WERE MADE AND MARKERS PLACED

PLATE 2-15 SERPENTINE CABLE SHAPE ON ICE PRIOR TO THE TOW

PLATE 2-16 ACTUAL TOW THROUGH UNBROKEN LEVEL ICE

PLATE 2-17 STRESS RELIEF CRACKS TO STBD OF MOBILE BAY GENERALLY ENDED DATA COLLECTION

PLATE 2-18 RADAR VIEW OF TRACKS AFTER TEST

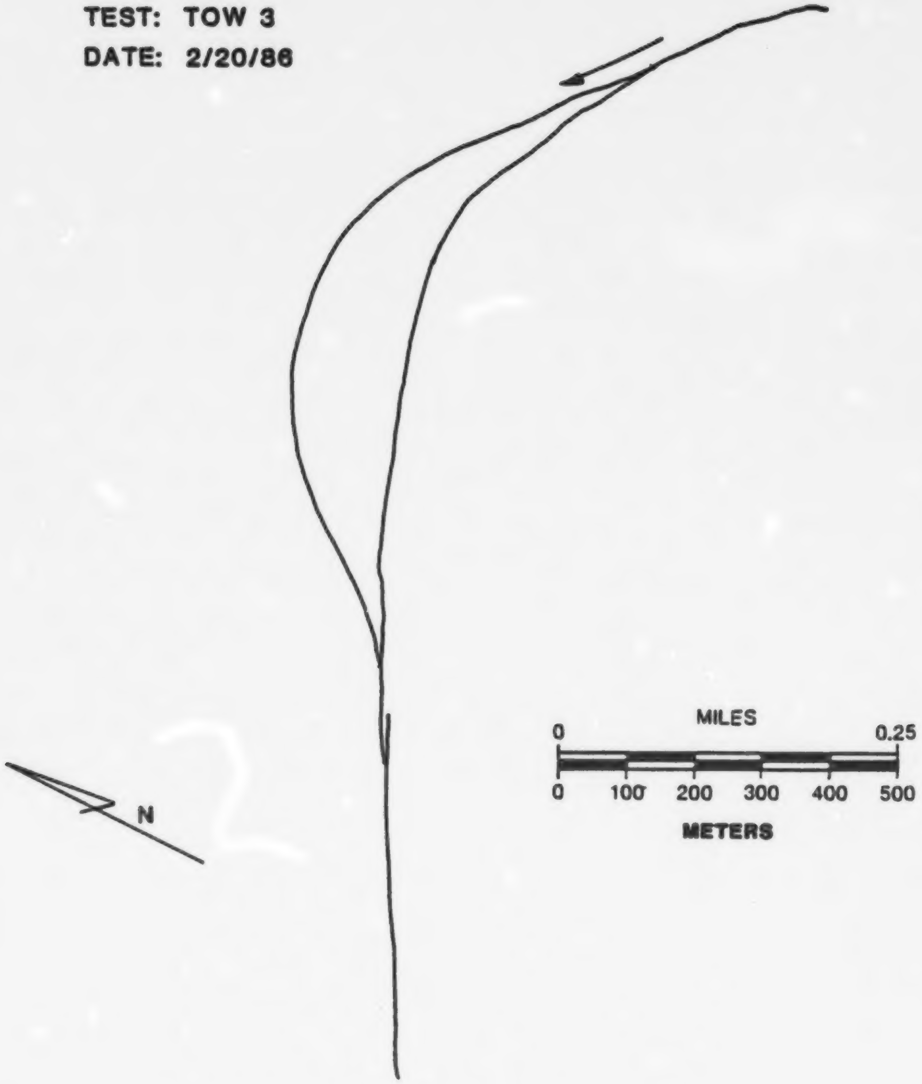

TEST: TOW 3
DATE: 2/20/86
N
MILES
0
0.25
0
100
200
300
400
500
METERS

Figure 2.3-2

TRACING OF TEST TRACK FROM MOBILE BAY'S RADAR

In addition to the described procedures, an attempt was made to measure the under-ice current in the test area. It was found that no meaningful currents were present, the vibration of the technician's hand being enough to obscure any velocity. Provisions were also made to remove surface snow from the test run area. However, snow removal was not carried out since only light and patchy snow conditions were observed, generally less than 5 cm thick. This amount of snow was of the same order of magnitude as that left by the snow blowers.

2.4 Ice Strength Measurements

In order to fully characterize the ice conditions prevalent during testing in-situ cantilever beams were tested to determine ice strength. These tests were conducted using the apparatus shown in Figure 2.4-1.

In order to determine ice strength and strain rates the following data was required from the beam tests:

- Hydraulic Cylinder Pressure
- Beam Dimensions
- Beam Deflection

The pressure data was obtained using a diaphragm pressure transducer with a visual gage as backup. The displacement was measured using an LVDT. These sensors were controlled and filtered using Vishay 2310 amplifiers similar to those used onboard MOBILE BAY. Data from the transducers was recorded using a two-channel thermal strip chart recorder. The amplifiers and recorders are shown in Plate 2-19.

The measurement of ice strengths was performed using personnel and equipment deployed from MACKINAW. These measurements proved to be time consuming, and were generally performed in the evenings or in the morning while MOBILE BAY was performing self-propelled trials. The general procedure was to unload equipment onto the ice beside MACKINAW and move it a safe distance away to an area of smooth ice. The loose surface snow was then cleared and the beams to be tested were laid out as a function of a sample thickness measurement. Plate 2-20 shows a beam being cut using a chainsaw, including clear area on three sides. Once the beam was cut, holes for toggles were made and the load frame was situated above the beam. Power for the load frame and instrumentation was provided by a portable generator. After all sensor were zeroed the pump was activated and load applied to the beam until it failed. Plate 2-21 shows a beam immediately following a test. Beam dimensions were measured after the test to reflect actual length and thickness. This process would be repeated 2-3 times in an average location.

PLATE 2-19 CHART RECORDER AND AMPLIFIERS FOR BEAM TESTS

PLATE 2-20 CUTTING BEAMS USING CHAINSAW

PLATE 2-21 BEAM SETUP WITH BEAM FLOATING AFTER A TEST

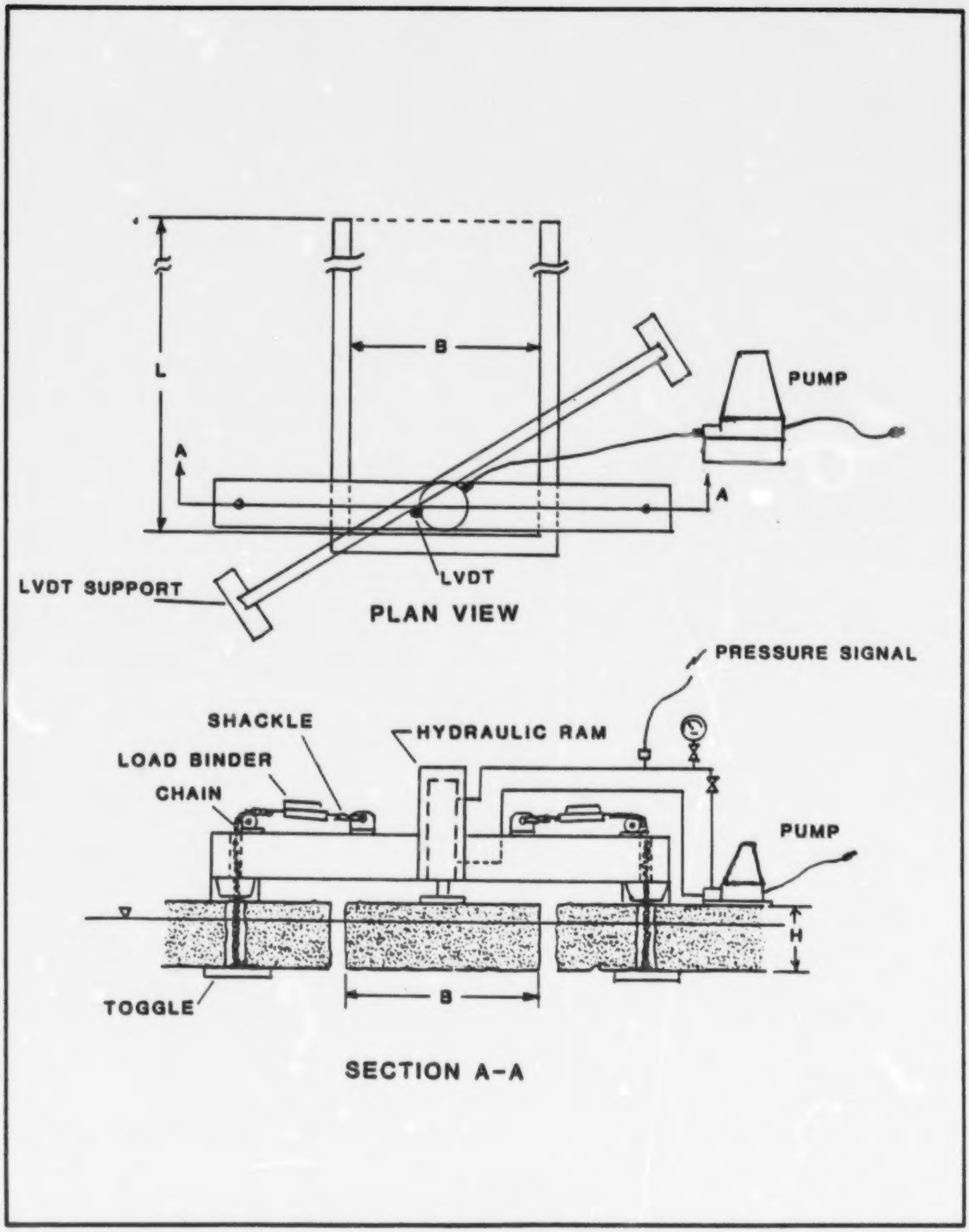

L
B
PUMP
A
A
LVDT SUPPORT
LVDT
PLAN VIEW
PRESSURE SIGNAL
SHACKLE
HYDRAULIC RAM
LOAD BINDER
CHAIN
PUMP
H
TOGGLE
B
SECTION A-A

Figure 2.4-1

FLEXURAL STRENGTH APPARATUS

2.5 Log of Daily Activities

The following is a day-by-day description of project activities as they occurred. The narrative does not include the predeployment meetings and instrumentation of MOBIL BAY, which took place earlier in February.

Sunday, 16 February 1986

Test personnel arrive at Sturgeon Bay and Cheboygan to meet MOBILE BAY and MACKINAW.

Monday, 17 February 1986

Instrumentation set up on board MOBILE BAY at Sturgeon Bay. Calibrations and system checkout. Left for Rock Island Passage in late PM.

Environmental gear loaded aboard MACKINAW at Cheboygan. Depart for Rock Island Passage at dusk.

Tuesday, 18 February 1986

MOBILE BAY and MACKINAW rendezvous north of Rock Island. Ice thickness 45cm-56cm (19"-22"). Late morning and early afternoon devoted to operational trials of towing procedures. Late afternoon: first beam strength test.

MOBILE BAY DRAFTS:
3.43m (11'3") FWD
3.81m (12'6") AFT

Weather foggy and overcast with average temperatures of 4°C (40°F) and winds 0-5 knots from the NNW.

Wednesday, 19 February 1986

Morning saw continued trials with ships in position for Tow-1 at noon. Test successfully completed in early afternoon, but load pin damaged during cable retrieval. More strength testing in afternoon and pin repaired.

Thursday, 20 February 1986

Two towed tests and three strength tests, still in area north-northwest of Rock Island.

Weather overcast with temperatures dropping below -7°C (20°F) and winds 15-25 knots from NNW.

Friday, 21 February 1986

Three more towed tests completed in the 48cm-56cm (19"-20") thick ice north of Rock Island. Snow cover was intermittent from 0-8m (0-3").

MOBILE BAY departed test area for Escanalos to perform escort operations, disembark observers, and obtain spare parts for test equipment. During evening passage self-propelled data was collected.

Weather clear with temperatures averaging -8°C (18°F) and winds 0-10 knots from the North.

Saturday, 22 February 1986

MOBILE BAY completed escort operations in AM and rendezvoused with MACKINAW in new op area west of Minneapolis shoal. All instrumentation recalibrated. Two towed tests in 30cm-38cm (12"-15") ice with 0-5cm (0-2") snow cover completed in the afternoon.

Weather overcast with -1°C (30°F) average temperature. Wind out of the WNW at 5-10 knots.

Sunday, 23 February 1986

Towed test conducted in 38cm (15") ice west of Minneapolis shoal in the morning. Afternoon devoted to self-propelled tests of MOBILE BAY and strength tests off MACKINAW.

Weather was partly cloudy with temperatures near -1°C (30°F) and winds out of the west at 0-5 knots.

MOBILE BAY DRAFTS:
3.28m (10'9") FWD
3.76m (12'4") AFT

Monday, 24 February 1986

Morning devoted to self-propelled tests of MOBILE BAY in 30cm-43cm (12" - 17") ice adjacent to Minneapolis shoal light. Beams for ice strength taken at the same time from MACKINAW.

Three towed tests in 30cm-38cm (12"-15") ice in the afternoon. The electrical connection between the shackle and load cell was damaged during operation and rebuilt during the evening. However there was no damage to the load cell itself. A shunt calibration was performed and it was found to be within one percent of the shop calibration value.

Weather partly cloudy with temperatures averaging -1°C (30°F) and wind 0-10 knots from the SSW.

Tuesday, 25 February 1986

Three towed tests were accomplished during the morning in 36cm-41cm (14"-16") with 0-8cm (0-3") snow cover. During the afternoon test equipment was removed from MOBILE BAY and transferred to MACKINAW while final ice properties were obtained. Both ships departed for homeport in the late afternoon.

Weather was overcast with temperatures averaging 0°C (32°F) and winds from the SE at 5-15 knots. Snow began falling as the ships left Groton Bay.

3. TEST RESULTS

The tests described in Section 2 yielded three sets of results:

- towed resistance data
- self-propelled data
- ice strength data

Each of these is summarized in the following sections.

3.1 Towed Resistance Results

During the nine day trials period 16 towed resistance tests were performed. Only one test, Tow-11, was not usable, due to heavy relief cracking in the adjacent ice sheet. Two tests, Tow-8 and Tow-9, were long enough or had varied enough parameters to represent two distinct datapoints each. Thus 17 valid data points were obtained representing the resistance of the 140' WTGB in ice. These tests are summarized in Table 3.1-1.

The data reduction procedure to arrive at these results is relatively straightforward. Test Tow-6 is used as an example to describe the procedures and results. Figures 3.1-1a through 3.1-1e and Table 3.1-2 show the basic data collected for this run. The following paragraphs discuss the measurements and treatment of the important test variables:

- Thrust
- Speed
- Tow Line Tension
- Ice Thickness

THRUST: During each towed test, the propulsion plant on MOBILE BAY was operated as close to a zero thrust point as possible. By operating at the propeller advance speed in this manner it was intended to eliminate the effects of dragging a "dead" propeller. The residual thrust was taken into account in determining total hull resistance by:

$$R_{TOT} = P + T \qquad (3.1)$$

where:

R_{TOT} = Total Hull Resistance
P = Tow Line Pull
T = Propeller Thrust

The thrust signal, as well as all other signals, was examined over the entire run period (Figure 3.1-1b) to identify steady state regions.

SPEED: Speed over the test period from doppler radar (Figure 3.1-1a) was checked by manually measuring the transit time between the marker flags in the thickness survey which was carried out prior to each run. Values from the two methods were generally within 5% of each other. The variation in the speed traces was normally less than 10% for the steady state portions of each run.

TOWLINE TENSION: Towline tension was measured using the instrumented clevis pin as described earlier. As seen in Figure 3.1-1e, a regular oscillation was observed in the tension readings. It is felt that these oscillations are due to the complex spring-mass system of the two ships and the cable between them. Figure 3.1-2 shows the system. A 14 second oscillation period is observed. It was postulated that the cable would be on the bottom during tests conducted in 25-30m (80-100 ft) water depths. This would result in a period of the right order. However, the high tensions involved make this unlikely. Since no measurements were taken of the length of cable in the water or of total length, it is not possible to verify this hypothesis. Preliminary calculations assuming no catenary give frequencies almost twice as high as those observed. Addition of catenary would reduce system stiffness and frequency, and therefore the proposed explanation remains possible.

ICE THICKNESS: The thickness of the ice along the intended test track was measured at 30m (100 ft) intervals. The data for Tow-6 is shown in Table 3.1-2.

Once all of the data was collected, a steady state period was selected as an analysis window. This was generally the longest possible time period during which the towing speed remained unchanged and during which the MOBILE BAY was fully in unbroken ice. There was no conscious attempt made to avoid portions of the time histories which exhibited more frequent or severe propeller-ice interactions. The time checks for speed verification were used to identify times associated with each flag location. For Tow-6, a period of 47 to 120 seconds was chosen, corresponding to the portion of the run between flags 2 and 7. The average thickness over this section was 35.8cm (14.1 in). Table 3.1-3 and Figures 3.1-3 through 3.1-6 show statistics and plots for the period of interest on Tow-6. Similar plots are reproduced for each test in Appendix B, and the mean values are tabulated in Table 3.1-1. The mean values have been used as the resistance data points in the discussion of results in Section 4. The standard deviations given in Appendix B are a measure of the error associated with the mean values of towed resistance.

TABLE 3.1-1

TOWED TEST RESULTS

DATE	TEST	DURATION(1) (sec)	SPEED (knots)	ICE THICKNESS(3) (m)	R_{TOT}(2) (N)
2/19	TOW-1	40	4.0	.523	108,612
2/20	TOW-2	59	5.0	.475	165,046
	TOW-3	130	2.5	.506	141,911
2/21	TOW-4	270	1.8	.506	102,402
	TOW-5	80	4.8	.457	160,963
	TOW-6	73	3.7	.358	64,655
2/22	TOW-7	135	2.8	.379	81,709
	TOW-8	35	6.3	.320	142,342
		32	6.8	.320	148,232
2/23	TOW-9	100	1.1	.379	74,311
	TOW-9A	100	1.3	.379	70,028
	TOW-10	100	4.9	.379	112,135
2/24	TOW-12	180	1.2	.330	49,949
	TOW-13	53	7.6	.381	166,215
2/25	TOW-14	180	2.1	.358	74,365
	TOW-15	30	7.4	.424	168,382
	TOW-16	60	4.4	.394	94,369

NOTES: (1) Length of reduced data period

(2) Derived from tow tension and thrust as

$$R = P + T$$

(3) Thickness based on mean of 11 measurements

TABLE 3.1-2

ICE THICKNESSES FOR TEST TOW-6

FLAG #	DIST (m)	SNOW COVER (cm)	ICE THICKNESS (cm)
1	0	2.5	38
2	30.5	2.5	33
3	61.0	5.0	38
4	91.5	1.3	36
5	122.0	trace	39
6	152.4	trace	28
7	182.9	2.5	41
8	213.4	1.3	38
9	243.9	3.8	33
10	274.4	1.3	33
11	304.9	1.3	36

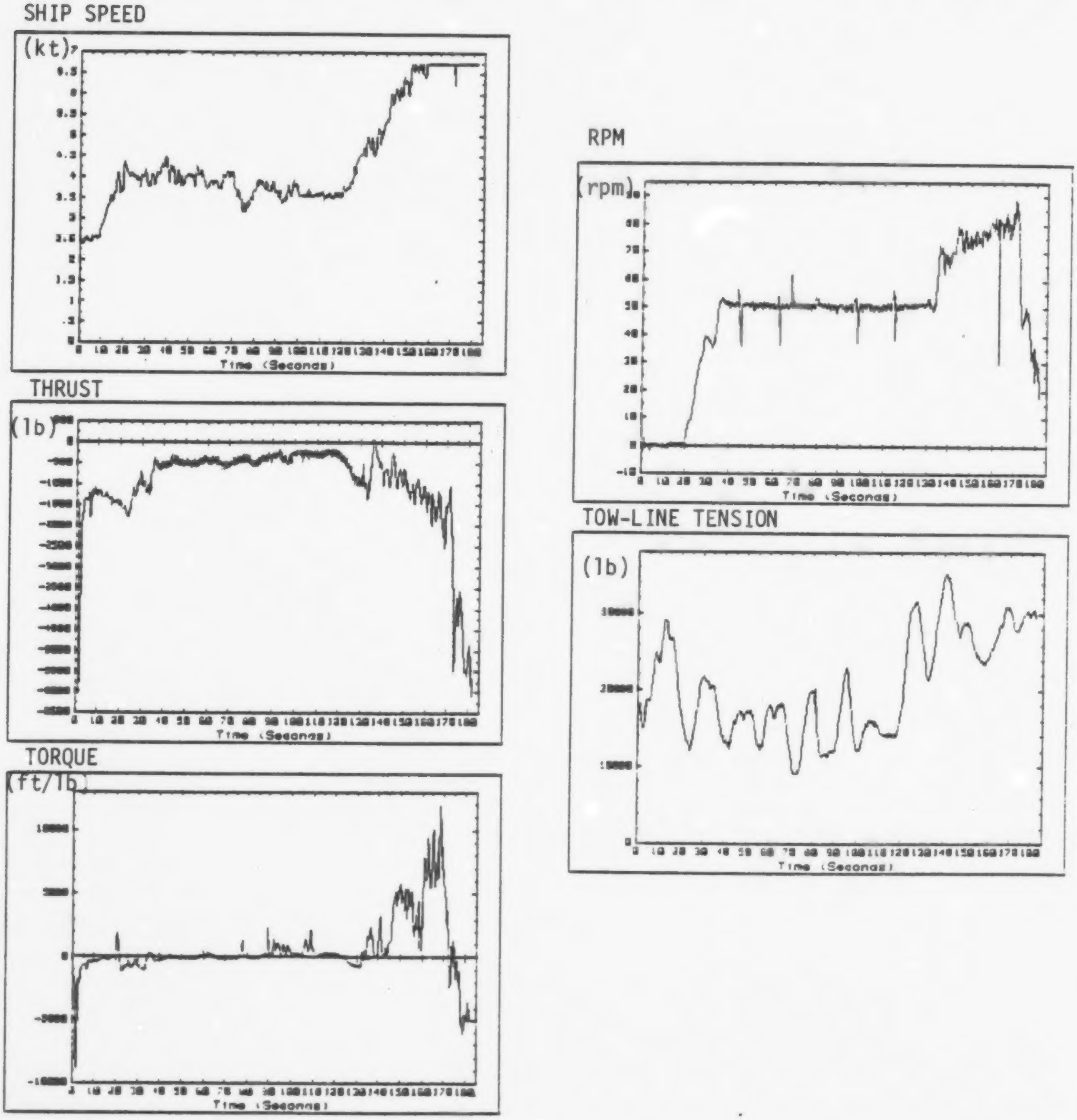
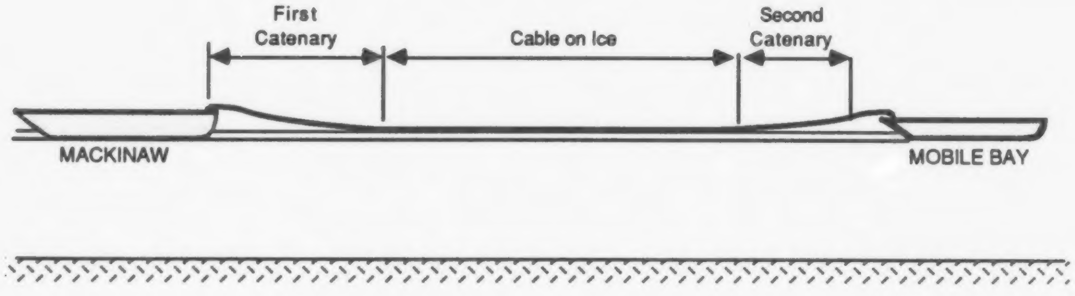
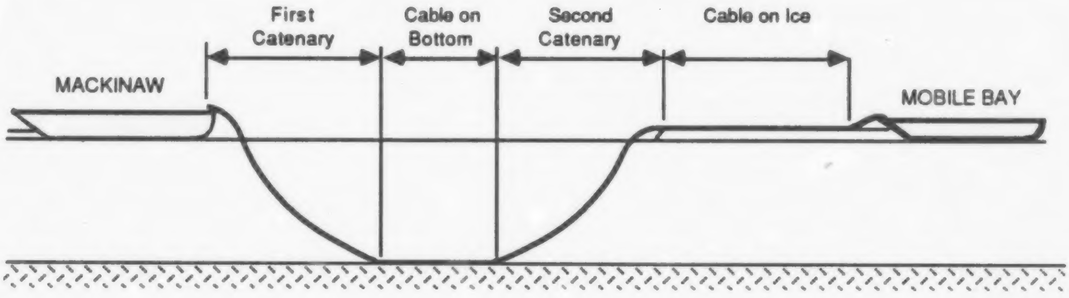


Figure 3.1-1a-e

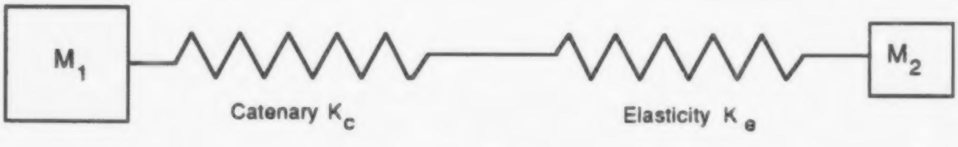
REPRESENTATIVE TOWING DATA


First Catenary
Cable on Ice
Second Catenary
MACKINAW
MOBILE BAY

USUAL CABLE CONFIGURATION DURING TOW


First Catenary
Cable on Bottom
Second Catenary
Cable on Ice
MACKINAW
MOBILE BAY

CABLE CONFIGURATION NEAR END OF TOW


M_1
M_2
Catenary K_c
Elasticity K_e

MASS-SPRING ANALOGY

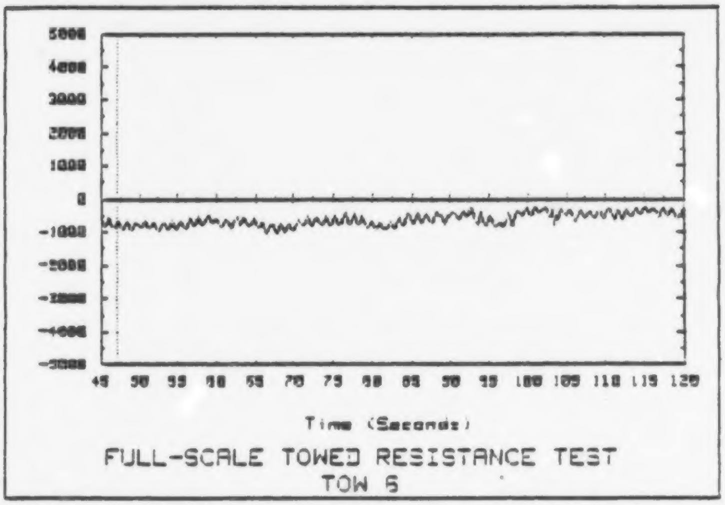
Figure 3.1-2

TABLE 3.1-3

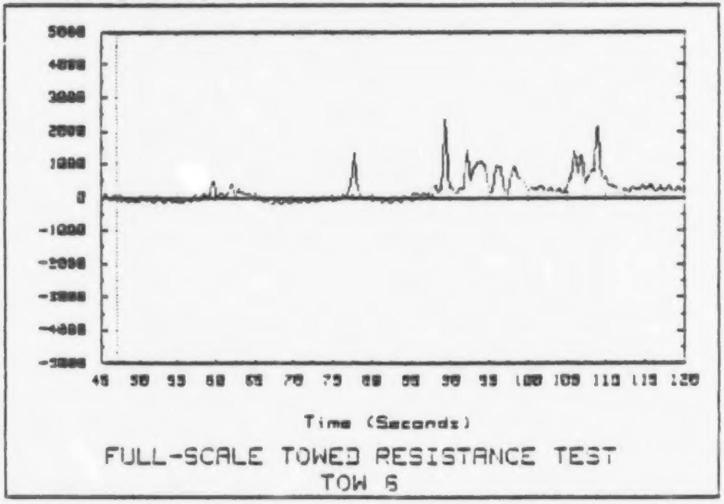
```
Test Results for Test TOW_6:  02/21/86, 16:59:15
                For the Interval Between  47  sec and  120  sec

   CHANNEL                              MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                         -231.9     -1037.1     -616.3       191.1
 2  Torque (ft-lbs)                      2330.6      -207.3      236.1       398.4
 3  RPM (rpm)                              61.7        36.3       50.5         1.9
 4  Ship Speed (kts)                        4.3         3.2        3.7          .2
 5  Tow-Line Tension (lbs)              23023.6      9056.6    15151.0      2903.7
 6  Net Resistance (lbs)                22507.5      8209.0    14534.7      2874.9
```

```
                Test Results for Test TOW_6:  02/21/86, 16:59:15
                For the Interval Between  47  sec and  120  sec

               Average Ship Speed                 3.7   k'ts
               Average Thrust                  -616.3   lbs
               Average Torque                   236.1   ft-lbs
               Average RPM                       50.5   RPM
               Average Tow-Line Tension       15151.0   lbs
               Average Net Resistance         14534.7   lbs
```

THRUST (lb)



TORQUE (ft-lb)



RPM (rpm)

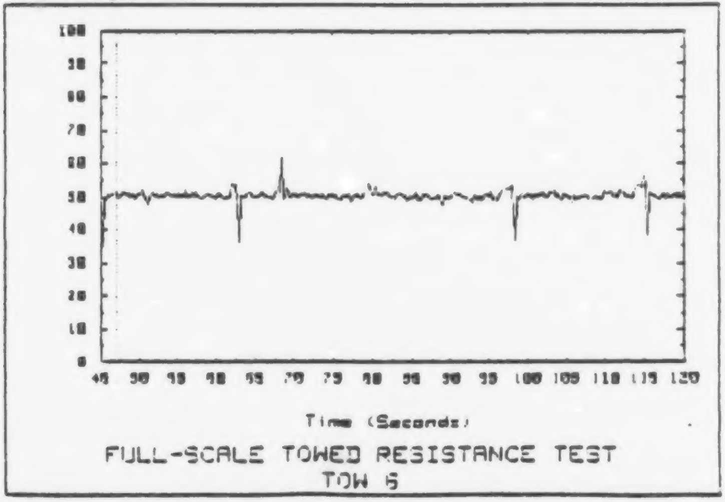


Figure 3.1-3

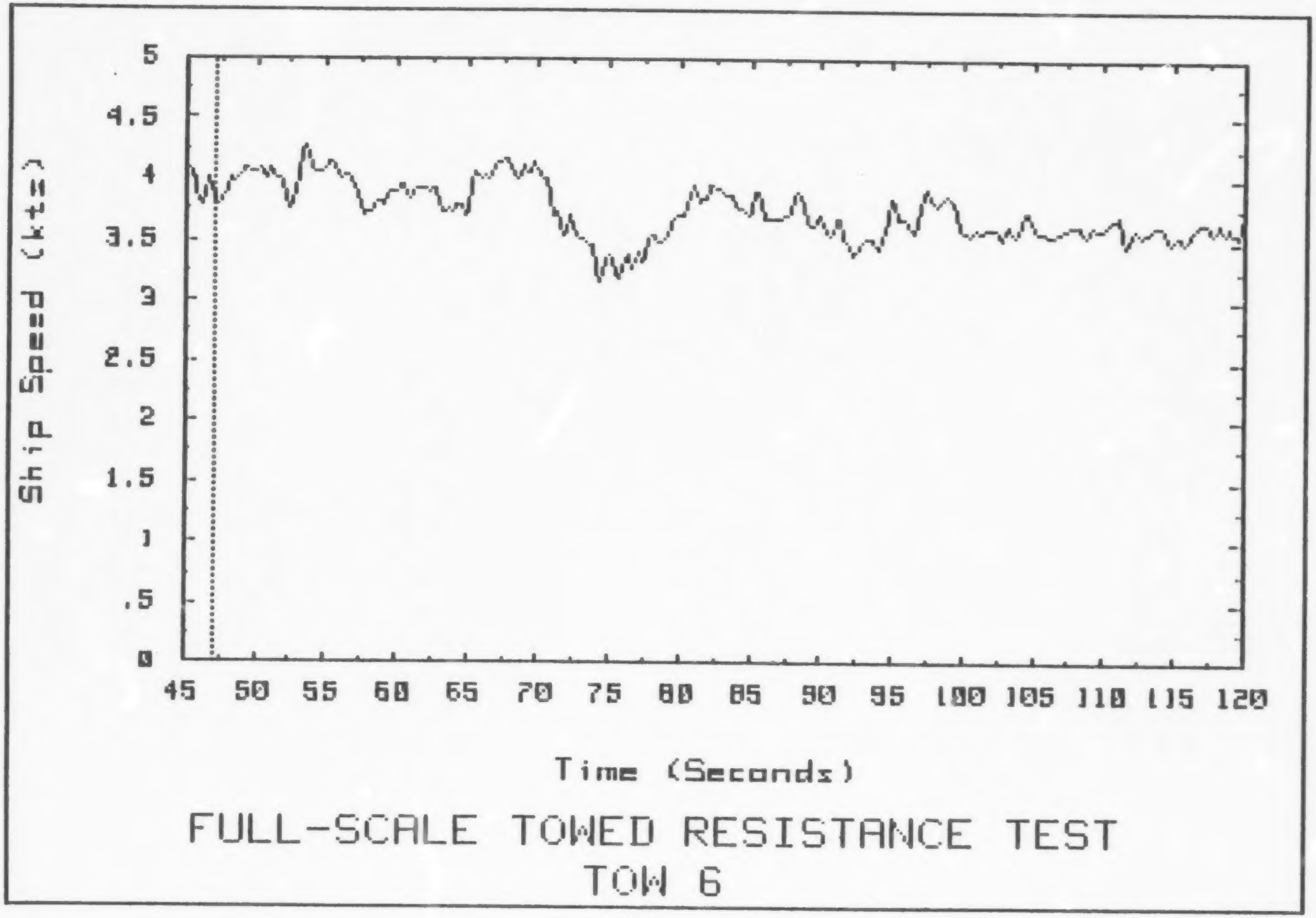

Ship Speed (kts)
5
4.5
4
3.5
3
2.5
2
1.5
1
.5
0
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
Time (Seconds)
FULL-SCALE TOWED RESISTANCE TEST
TOW 6

Figure 3.1-4

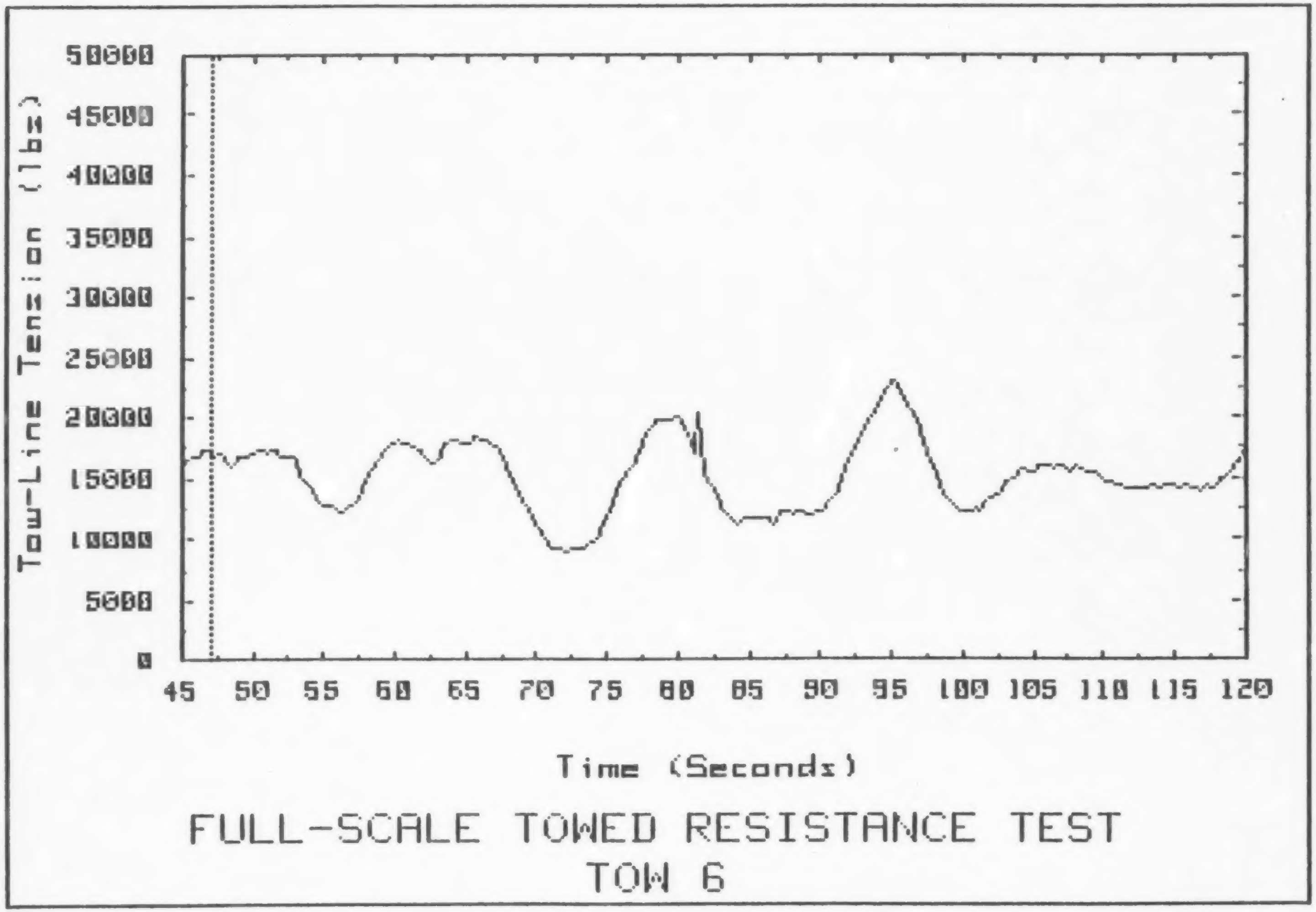
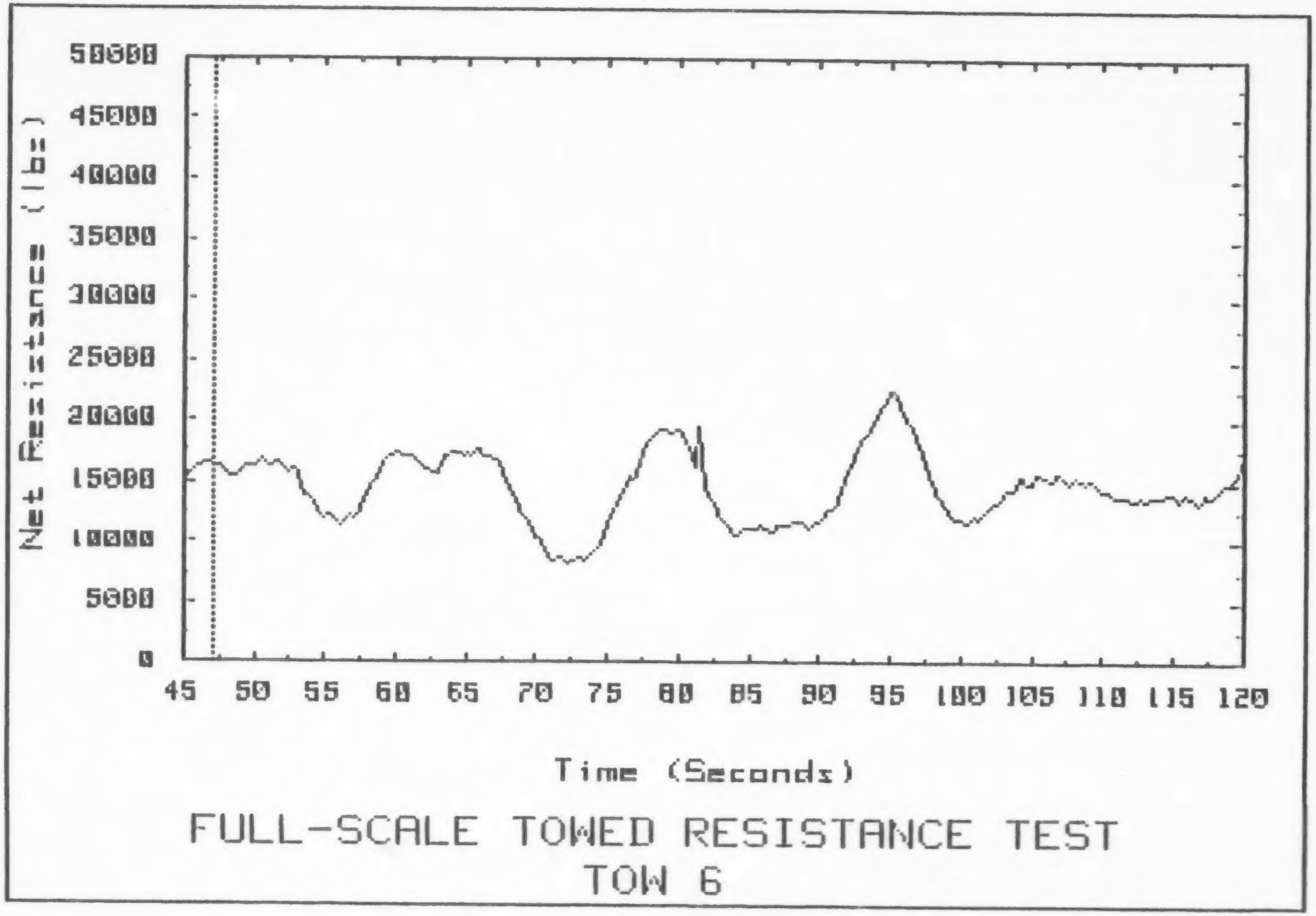

Tow-Line Tension (lbs)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
Time (Seconds)
FULL-SCALE TOWED RESISTANCE TEST
TOW 6

Figure 3.1-5



FULL-SCALE TOWED RESISTANCE TEST
TOW 6

Figure 3.1-6

3.2 Self-Propelled Results

A total of 31 self-propulsion points were obtained on three separate days. These are shown in Table 3.2-1. A typical test contains one, two, or three data points, differentiated by speed and power. As in the case of the towed tests, data points were identified as mean averages over the steady state periods identified.

Figure 3.2-1 shows time series data plots for a typical test, SP-17. Only torque, RPM, and ship speed are shown. Variability in these parameters, as in the case of the towed tests, was very low.

Table 3.2-2 and Figures 3.2-2 through 3.2-5 show the results for the period from 211 to 403 seconds, designated SP-17B. The average values represent the basic results for these tests. The derived values listed are covered in the analysis portion of this report. Similar sets of tables and plots for each of the 31 data points can be found in Appendix D.

Two confinement conditions are represented in the self-propulsion data. The majority of points were derived from tests where the ship followed tracks in the ice which may allow pressure relief. This test configuration was chosen to be consistent with the towed resistance procedure, which also allows pressure relief. A second set of thrust data was derived from trials which did not experience pressure relief. Although there is an insufficient number of data points on which to base a detailed analysis, it appears from comparing similar tests that there is no significant difference between the two sets of thrust data.

Error estimates have not been included in Table 3.2-2, but are available for each test in Appendix D. The standard deviations are generally less than 3 percent of the mean value of thrust and less than 8 percent of the mean value of torque.

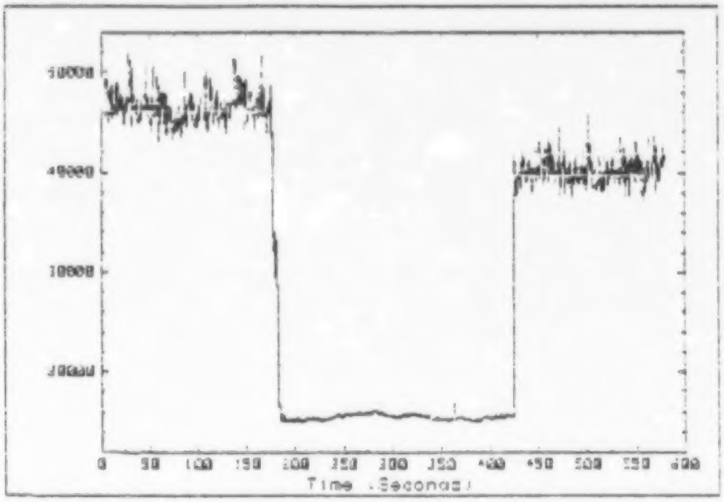
TABLE 3.2-1

SELF-PROPELLED RESULTS

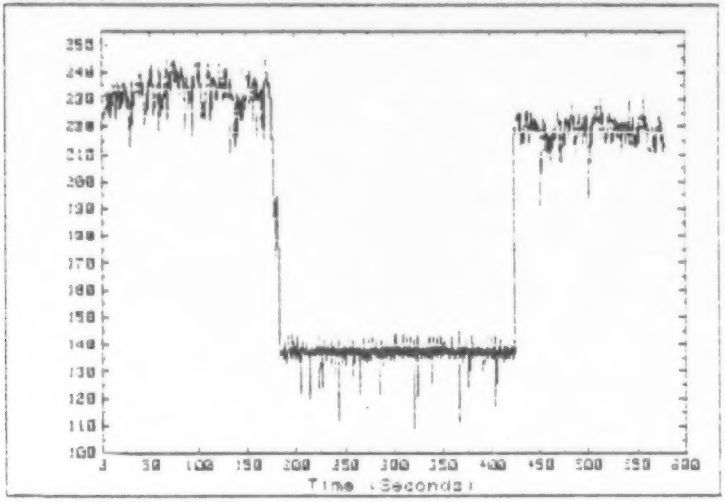
DATE	TEST	SPEED (knots)	THICKNESS (m)	THRUST (N)	TORQUE (Nm)	RPM	SHP (kw)
2/21	SP-1	3.3	0.470 (1)	180,139	56,285	216.9	1278
	SP-2a	1.8	0.470 (1)	116,209	32,349	168.6	571
	SP-2b	4.8	0.470 (1)	205,871	73,433 (2)	243.2	1870
	SP-3	3.7	0.470 (1)	171,002	57,073	215	1285
	SP-4	5.5	0.470 (1)	198,776	74,353 (2)	246	1915
	SP-5a	5.7	0.483 (1)	152,546	55,515	216.9	1260
	SP-5b	4.1	0.483 (1)	98,995	31,044	168.2	547
	SP-5c	6.3	0.483 (1)	180,595	61,462	233.9	1504
2/23	SP-6a	3.3	0.394	120,168	32,169	178.7	602
	SP-6b	6.5	0.356	205,943	66,580	249.7	1740
	SP-6c	5.4	0.330	170,068	52,333	222.7	1220
	SP-7a	4.9	0.343	145,642	40,503	204.3	867
	SP-7b	6.0	0.313	182,300	56,388	233.6	1379
	SP-7c	0.4	0.394	86,228	18,675	138	270
	SP-8	5.2	0.381	170,588	54,513	219	1250
	SP-9A	2.4	0.279	97,308	24,315	154	391
	SP-9B	4.3	0.267	143,022	43,413	200	907
	SP-10A	5.5	0.318	164,010	54,072	220.1	1246
	SP-10B	3.1	0.394	108,193	29,058	169.6	516
2/24	SP-11	5.4	0.356	166,901	55,730	218.3	1274
	SP-12	6.8	0.318	201,539	73,318 (2)	249.5	1915
	SP-13	3.2	0.330	105,982	30,595	168.7	541
	SP-14	4.5	0.330	137,472	44,396	198.2	921
	SP-15a	5.3	0.432	162,777	55,460	220.9	1282
	SP-15b	3.1	0.381	105,547	31,208	170.4	557
	SP-16a	4.3	0.381	137,231	45,221	199.1	943
	SP-16b	5.8	0.457	175,757	63,506	232.2	1543
	SP-16c	1.1	0.445	76,651	21,324	137.7	307
	SP-17a	6.0	0.407	175,268	63,118	233.4	1542
	SP-17b	1.0	0.318	74,783	21,005	137.1	301
	SP-17c	5.0	0.381	159,143	54,633	218.6	1251

Notes: (1) Thickness for 2/21 Tests Unreliable
(2) Torque Measurement System Overranged

TORQUE (ft-lbs)



RPM (rpm)



SHIP SPEED (kt)

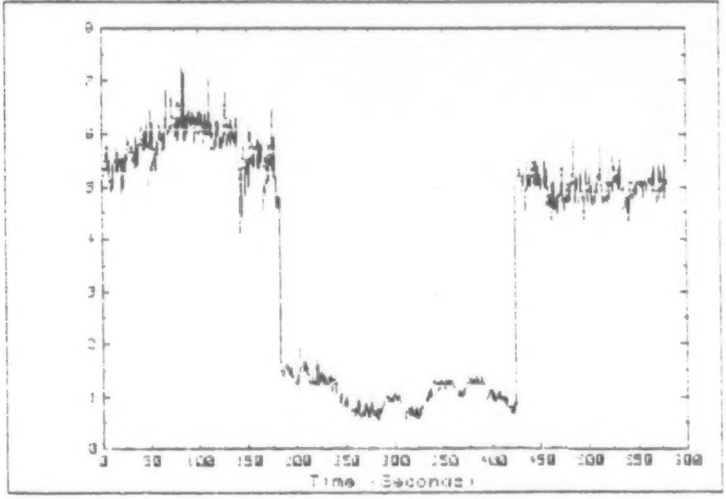


Figure 3.2-1
RAW DATA FOR SELF PROPELLED TEST SP-17 (2/24/86)

TABLE 3.2-2

```
              Test Results for Test SP_178:  02/24/86, 11:04:43
              For the Interval Between  211  sec and  403  sec

   CHANNEL                              MAXIMUM      MINIMUM       MEAN       STDRD DEV

 1  Thrust (lbs)                        17675.8      15169.0      16812.3        391.9
 2  Torque (ft-lbs)                     16784.2      14992.4      15492.6        299.5
 3  RPM (rpm)                             144.8        109.5        137.1          2.8
 4  Ship Speed (kts)                        1.7           .5          1.0           .2
 6  Shaft Horsepower                     436.8        325.2        404.3         10.5


              Test Results for Test SP_178:  02/24/86, 11:04:43
              For the Interval Between  211  sec and  403  sec

             Average Ship Speed                  1.0   kts
             Average Thrust                  16812.3   lbs
             Average Torque                  15492.6   ft-lbs
             Average RPM                       137.1   RPM
             Average Shaft Horsepower          404.3   HP
             Average Ice Thickness            1.0417   ft
             Mean Advance Coeff., Js          0.0880
             Thrust Coefficient, Kt           3.182E-01
             Torque Coefficient, Kq           3.449E-02

--------------------------------------------------------------------------------

                           RESISTANCE FORM 1             RESISTANCE FORM 2

Total Resistance,lbs           9.993E+03                     1.114E+04
Thrust Deduction               4.651E-01                     3.373E-01
Propulsive Coeff.              6.914E-02                     6.566E-02

--------------------------------------------------------------------------------

                             Thrust Identity               Torque Identity

Advance Coefficient            -0.1114                      -0.0144
Thrust Coefficient              3.182E-01                    2.386E-01
Torque Coefficient              3.831E-02                    3.449E-02
Advance Velocity,fps           -2.16                        -.29
Effective Wake                  2.265E+00                    1.164E+00
Open Prop Eff.                 -1.473E-01                   -1.920E-02
Relative Rotative Eff           1.111E+00                    1.102E+00
Hull Efficiency (Res. Form 1)  -4.226E-01                   -3.262E+00
Hull Efficiency (Res. Form 2)  -5.238E-01                   -4.041E+00
```

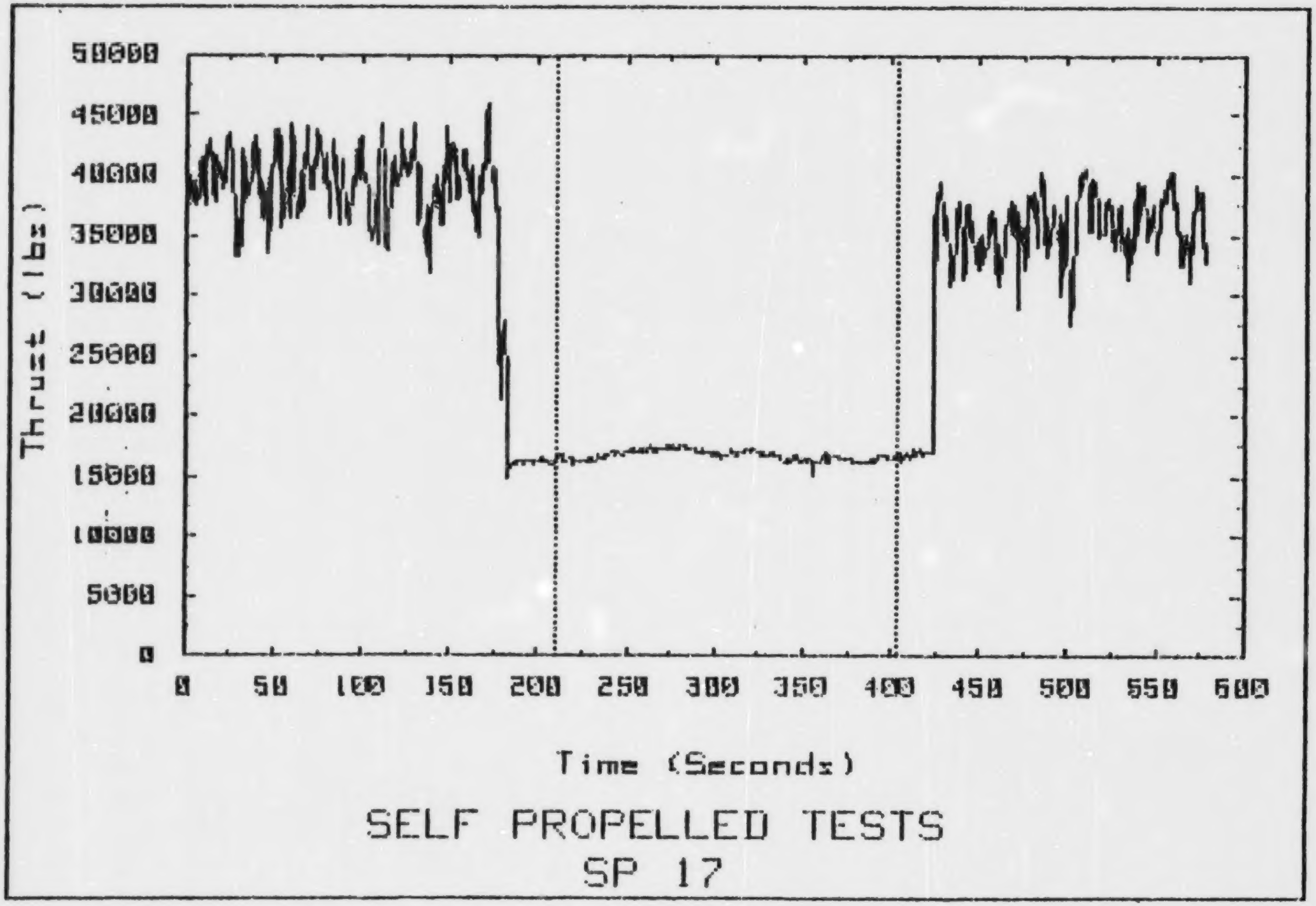
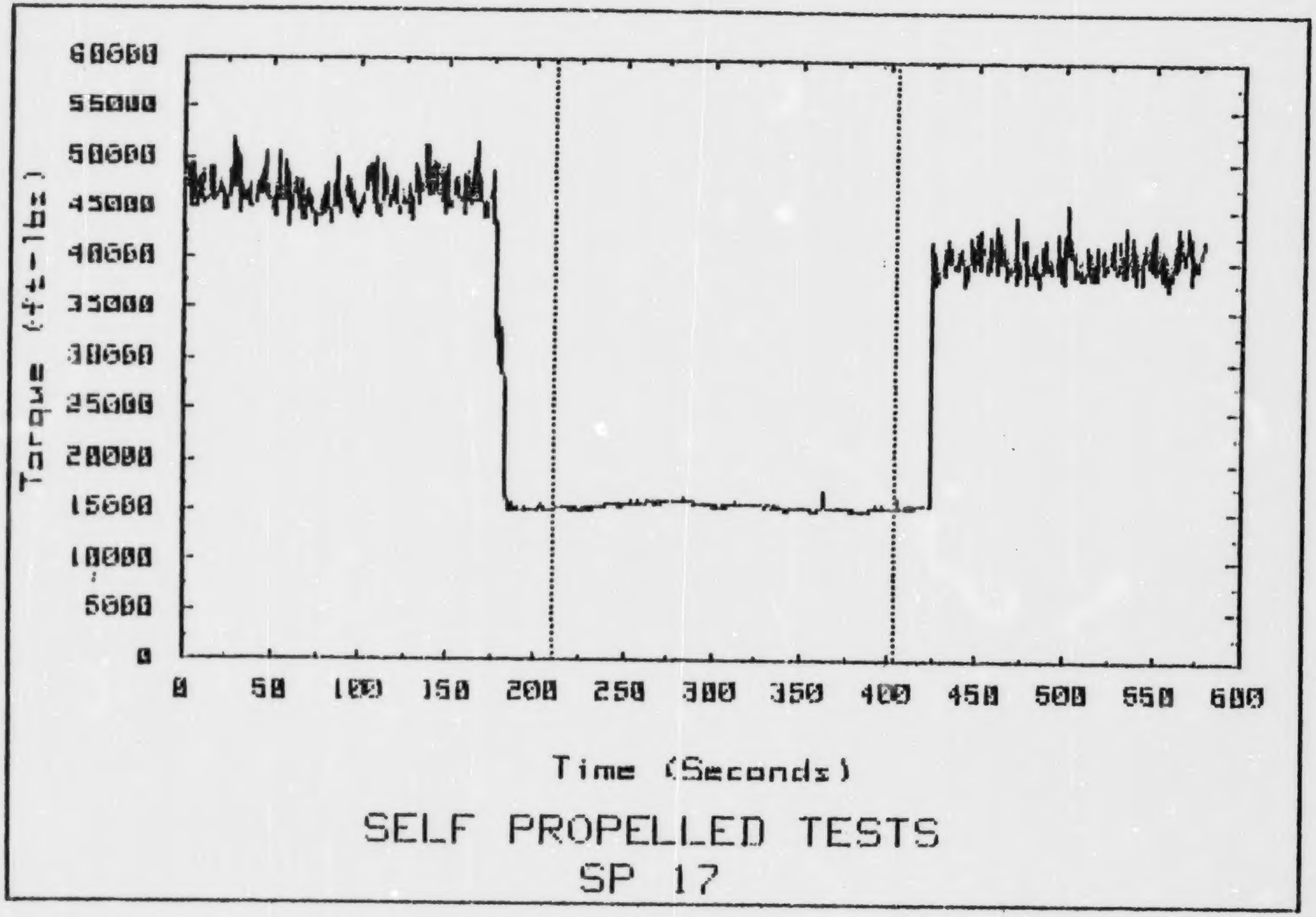

Thrust (lbs)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (Seconds)
SELF PROPELLED TESTS
SP 17

Figure 3.2-2



SELF PROPELLED TESTS
SP 17

Figure 3.2-3

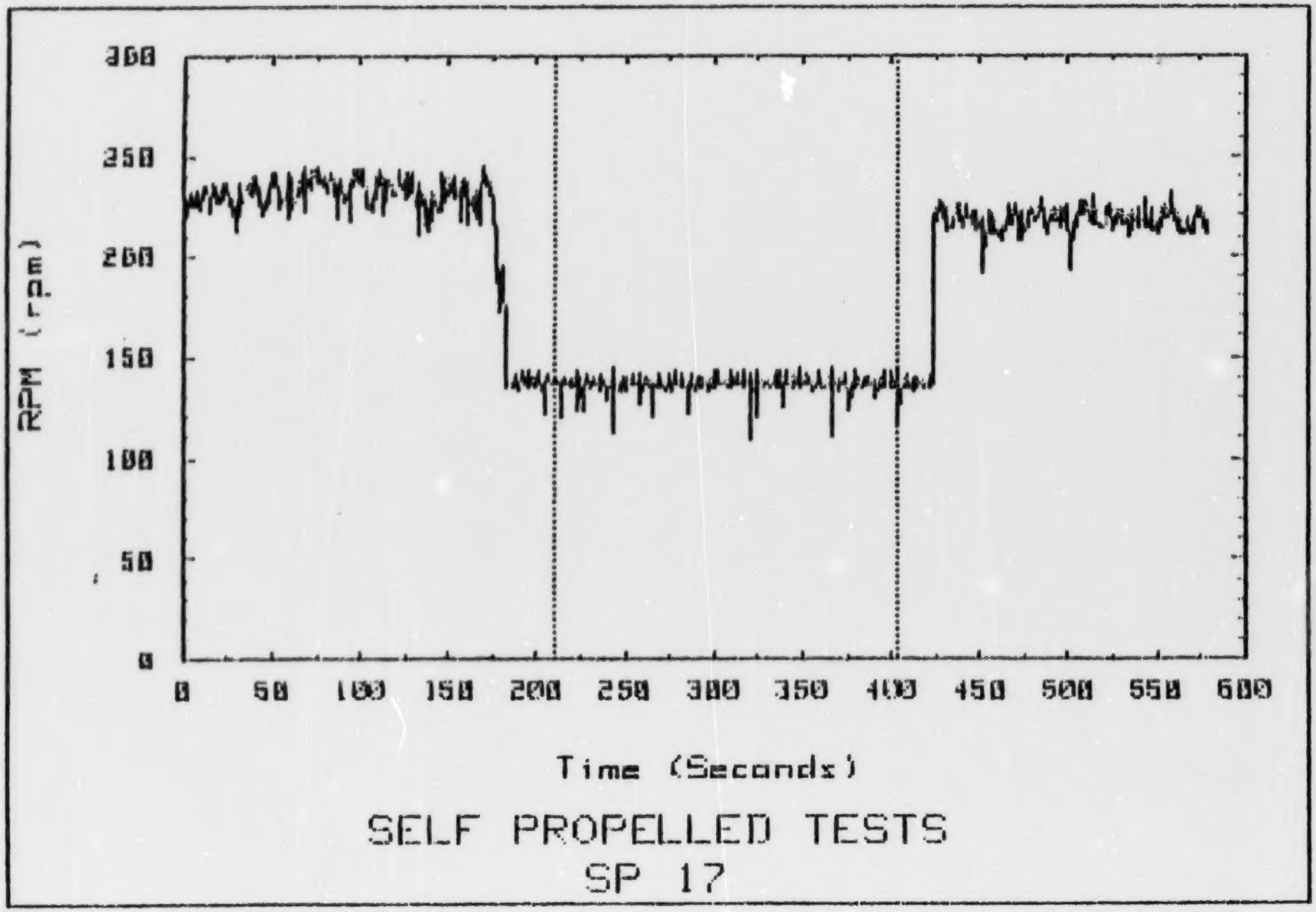

RPM (rpm)
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (Seconds)
SELF PROPELLED TESTS
SP 17

Figure 3.2-4

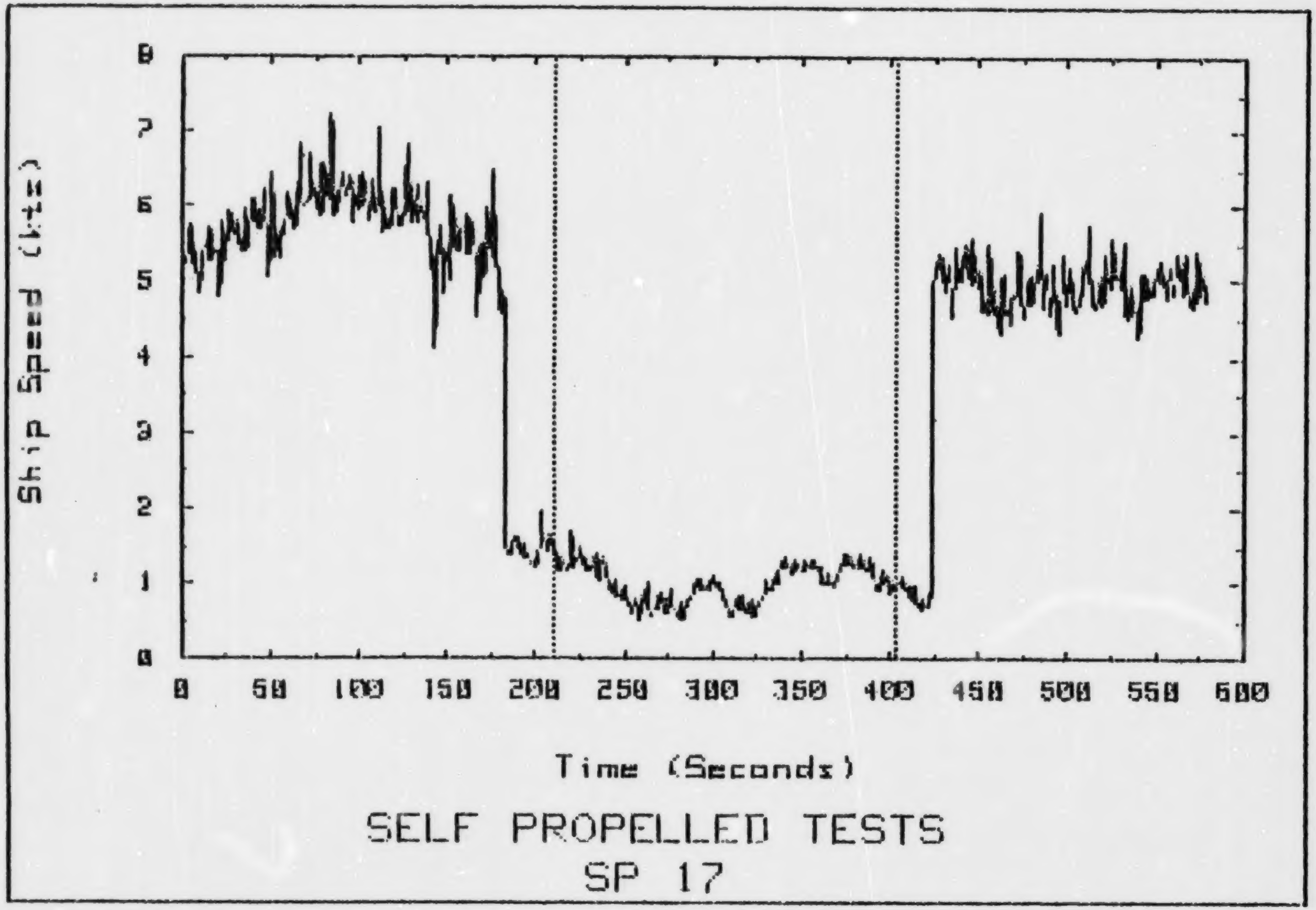

Ship Speed (kts)
0
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (Seconds)
SELF PROPELLED TESTS
SP 17

Figure 3.2-5

3.3 Ice Strength Results

Ice strengths were obtained by breaking in-situ cantilever beams using procedures and equipment described in Section 2. Strength calculations required only load and dimension estimates, while deflections were measured to monitor strain rates. Figure 3.3-1 shows a typical test trace.

Table 3.3-1 summarizes the strength data obtained. In a number of cases, instrumentation glitches prevented electronic load or deflection measurements. Primary load information was available, however, using a visual pressure gage. Inplane elastic modulus, E, can be estimated from the measured beam deflections given in Table 3.3-1. However it is cautioned that point loading methods, rather than beam tests are generally used in model test determination of E. Hence the beam test results from the MOBILE BAY trials would not be comparable to model scale E values.

No correlation between ice temperature and ice strength or air temperature at the time of testing was observed. A weak correlation with temperature trends over the previous 24 hours was indicated. No correlation of resistance to various ice strengths (admittedly a small range) was noted.

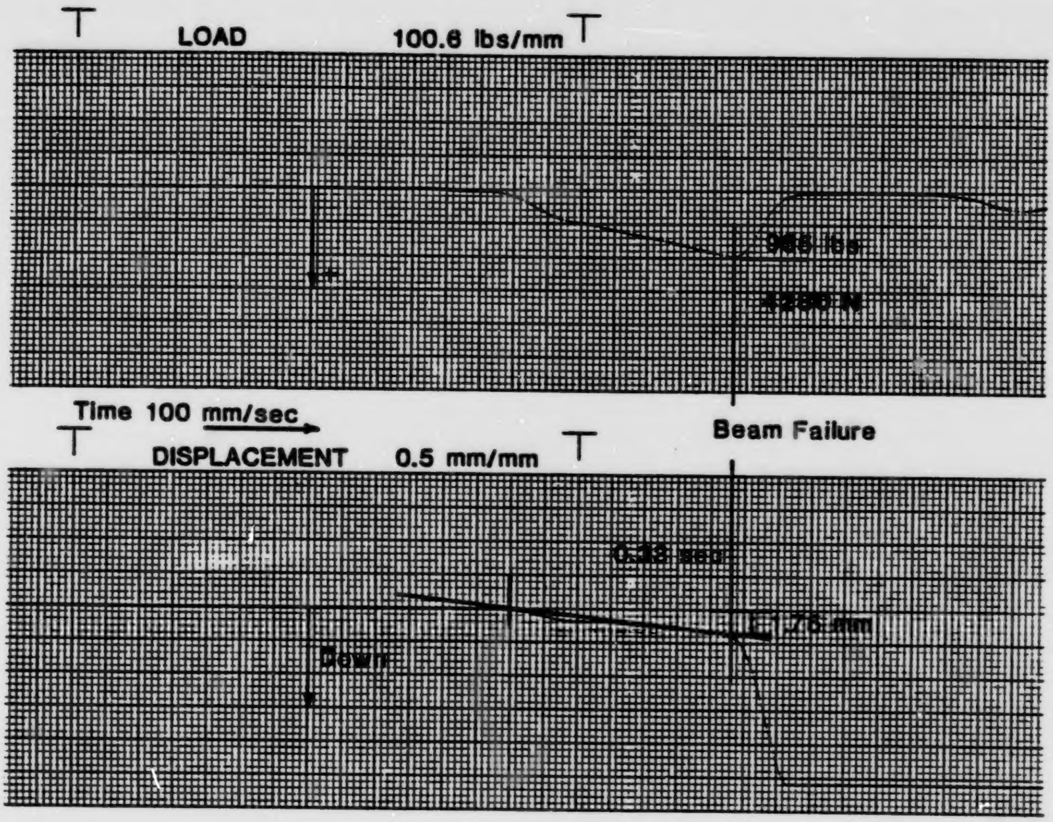


Figure 3.3-1

TYPICAL BEAM TEST TRACE (Beam 10 2/24/86)

TABLE 3.3-1

ICE STRENGTH TEST SUMMARY

DATE	BEAM #	ICE TEMPERATURE (°C)	LOAD (N)	BEAM (3) DIMENSIONS (cm)	STRENGTH (kPa)	DEFLECTION (mm)	STRAIN(5) RATE (1/sec)
2/18	1	-0.68	7828	53 x 108 x 203	283.4	1.65	.0022
2/19	2(1)						
	3	-0.69	6984(2)	50 x 102 x 211	328.8		
2/20	4	-2.9	5596	51 x 102 x 318	390.2		
	5	-1.71	4697	53 x 102 x 366	355.5		
2/23	6	-0.66	4190(2)	43 x 89 x 338	487.8		
	7	-0.66	4190(2)	43 x 89 x 340	476.2		
	8	-0.66	2015	43 x 89 x 244	166.6(4)		
2/24	9	-1.57	3132	38 x 76 x 305	485.5	1.5	.0086
	10	-1.57	4248	38 x 76 x 300	652.9	1.75	.0070
	11	-1.57	3132	41 x 82 x 351	442.7	1.70	.0105
	12	-1.57	4026	38 x 76 x 305	634.3	1.49	.0115
2/25	13	-0.61	7166	41 x 82 x 351	498.6		
	14	-0.59	1793	32 x 82 x 330	408.4		
	15	-0.66	3696	43 x 85 x 340	447.0	1.04	.0042
				AVERAGE	453.5 kPa		.0073
				STD DEV	102.3 kPA		.0033

NOTES:

(1) Hydraulic Malfunction
(2) Loads from Dial Gage Backup
(3) H x B x L where L is length as broken
(4) Broke at flaw
(5) $\dot{\epsilon} = \frac{S}{\tau \, 2H}$

3.4 Propeller-Ice Interaction

It is fundamental to the understanding of propeller performance records to know whether or not any specific record includes the effects of interaction between the propeller and ice pieces. Table 3.4-1 is based on data in Appendix C and summarizes the frequency and severity of ice encounters with the propeller which were recorded during the towed resistance tests. During these tests the propeller was generally operated at a low RPM, just sufficient to counter the propeller drag. In this test condition the small measured thrust was found to be a good indicator of the occurrence of propeller-ice interactions. From the table, it can be observed that at speeds below 4 knots there are few encounters which have small magnitudes. Between 4 knots and 7.6 knots the frequency and severity of the encounters became progressively greater. A maximum frequency of 25.2 encounters per minute was observed for a speed of 6.8 knots during Tow 8A. The maximum thrust peak was estimated as 17,350 N below the mean and the standard deviation in thrust was 6,000 N. The corresponding standard deviation in Torque was 13,600 N. Figure 3.4-1 shows examples of thrust and torque time histories recorded during towing of MOBILE BAY.

The trends determined in the towed resistance tests provide additional information in estimating propeller-ice interactions in the self-propelled tests. In test SP-6b the speed was 6.5 knots in 0.356 m thickness of ice. The measured thrust was approximately 206,000 N and the torque was nearly 67,000 N-m. Based on the standard deviations and peak values of thrust and torque from towed test 8A in Table 3.4-1, it would be expected that the propeller-ice interactions would cause 3-8.4 percent variations in thrust and 20-60 percent variation in torque. The expected level of the interaction appears reasonable for thrust, but it is exaggerated for torque on the basis of the observed SP-6b time history. The severity in torque variation appears to be reduced at the higher RPM values occurring in the self-propelled tests. A percentage variation in torque of approximately 8.4 percent would appear more realistic.

It should be noted in Figure 3.4-1 that the RPM time history is taken directly from the ship tachometer. This is a DC generator giving a direct analogue measurement of shaft revolutions and therefore the RPM measurements are expected to be quite accurate. It is also interesting to note from Table 3.4-1 the RPM mean values required to produce a nominally zero thrust during the towed conditions. During Tow-8A at 6.77 knots a shaft rotation rate of 70.4 RPM was needed to overcome the drag of the MOBILE BAY propeller. In a corresponding self-propelled test, SP-6b, the propeller shaft rate was about 200 RPM.

NEGLIGIBLE PROPELLER-ICE
INTERACTION
SPEED: 3.7 knots

SIGNIFICANT PROPELLER-ICE
INTERACTION
SPEED: 7.6 knots

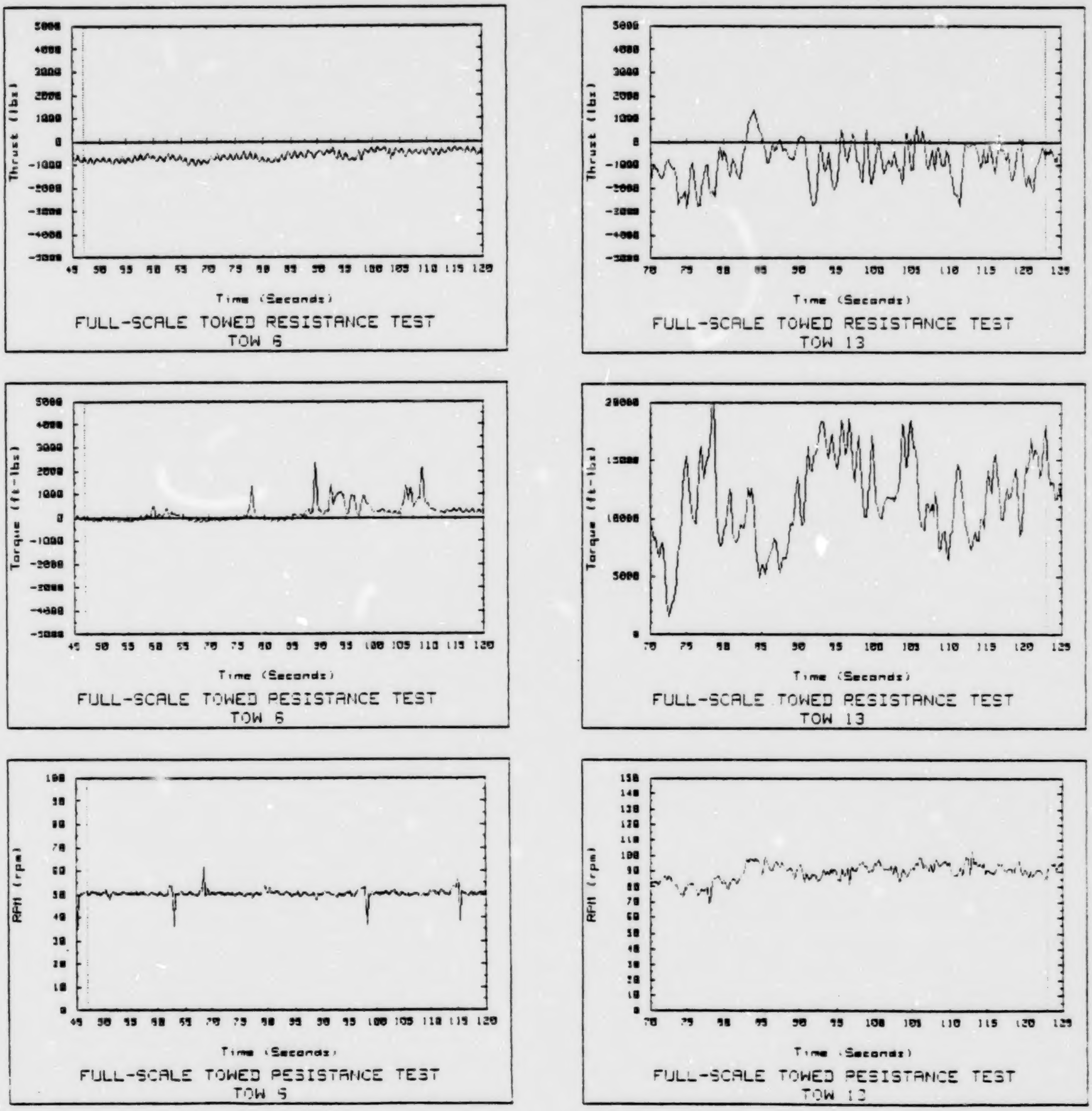


FIGURE 3.4-1

TABLE 3.4-1

PROPELLER-ICE INTERACTIONS DURING TOWED TESTS

TEST	SPEED	RPM	*ENCOUNTERS/ MIN.	MAX. SEVERITY THRUST (kN)	THRUST STANDARD (kN)	MEAN THRUST (kN)
Tow 1	4.0	9	15.0	-22.69	4.76	-8.45
2	5.0	60	16.0	-19.13	4.92	1.50
3	2.5	1	1.8	-11.12	2.05	3.26
4	1.8	0	0.6	- 8.01	1.16	7.22
5	4.8	58.2	12.8	-13.34	3.29	-3.07
6	3.7	58.2	0.0	- 1.78	0.85	-2.74
7	2.8	-0.1	1.7	- 4.89	0.80	0.30
8	6.3	63.5	13.5	-12.90	3.96	-0.73
8A	6.8	70.4	25.2	-17.35	6.01	-0.45
9	1.1	-.5	0.6	-3.56	0.44	6.75
10	4.9	66.9	-	-	-	2.67
12	1.2	0.1	0.0	-1.33	0.41	2.47
13	7.6	89.3	20.0	-8.90	3.79	-3.89
14	2.1	8.0	0.3	-	0.82	0.02
15	7.4	99.5	24.0	-8.01	3.69	1.09
16	4.4	43.8	8.0	-6.23	1.44	-4.01

---

* Encounter if peak thrust is more than 1 standard deviation from the mean value. Data extracted from Appendix C.

An attempt was made to estimate the effect of propeller-ice interaction on the self-propelled thrust by means of the 'zero thrust' data. An upper limit to its influence would assume that at higher speeds the ice interaction is entirely responsible for the thrust requirement, rather than propeller appendage drag. However, this was not found to be possible in the absence of overload open water propeller data. Based only on the available open water propeller data [equations 4.2.8], a negative value of K_T is calculated using the measured ship speed and propeller RPM from the towed tests, such as TOW-8A. Hence no meaningful estimate of a thrust correction could be derived.

While overload condition (open water) propeller tests are required for the above approximation, a more detailed assessment of the influence of the propeller-ice interaction would require full scale towed trials in clear water. A comparison between 'zero thrust' RPM data in the clear water towed condition and ice-covered water would better resolve the relative influence of ice ingestion and hydrodynamic propeller drag.

4.0 ANALYSIS

Extensive analysis of the test results has been undertaken. This analysis is intended to fulfill the following goals:

- Experimenting with appropriate non-dimensional representations of ice resistance.
- Investigation of the accuracy of model test predictions of both resistance and propulsion parameters.
- Examination of propulsion parameters with a view, in the future, to obtaining improved design information.

The following sections examine questions associated with ice resistance and propulsion parameters, respectively. Figure 4.0-1 shows the general approach to the analysis.

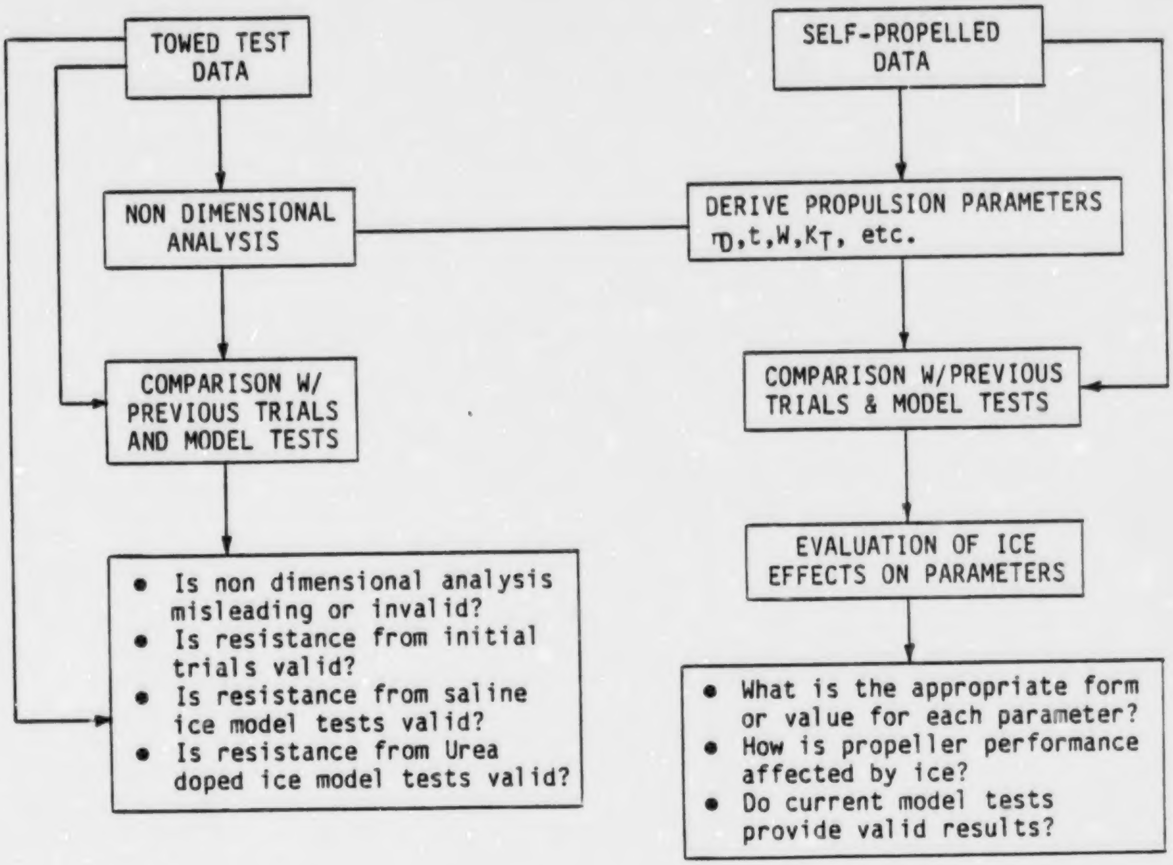

TOWED TEST DATA
NON DIMENSIONAL ANALYSIS
COMPARISON W/ PREVIOUS TRIALS AND MODEL TESTS
• Is non dimensional analysis misleading or invalid?
• Is resistance from initial trials valid?
• Is resistance from saline ice model tests valid?
• Is resistance from Urea doped ice model tests valid?
SELF-PROPELLED DATA
DERIVE PROPULSION PARAMETERS η_D,t,W,K_T, etc.
COMPARISON W/PREVIOUS TRIALS & MODEL TESTS
EVALUATION OF ICE EFFECTS ON PARAMETERS
• What is the appropriate form or value for each parameter?
• How is propeller performance affected by ice?
• Do current model tests provide valid results?

Figure 4. -1

ANALYSIS PROCEDURES

4.1 LEVEL ICE RESISTANCE

One of the primary goals of this program was to obtain a definitive data set for level ice resistance at full scale. This data has been analyzed to examine three critical questions.

1) What non-dimensional form is best suited to the description of level ice resistance?

2) Do model tests provide valid estimates of level ice resistance?

3) What resistance estimates may be used in determining propulsion parameters at full scale.

This section will discuss the analysis of the resistance data related to the first two questions, and will identify estimating procedures to be used in the analysis of the self-propelled trials.

4.1.1 Analysis of Measured Resistance

Many investigators, in particular Lewis, Vance, and and Edwards [13,14,15] have made a concerted attempt to rationalize the analysis of level ice resistance and thereby provide approximation methods for use in design. It has long been recognized that the number of variables which might have an influence on ice resistance is overwhelming. We have depended heavily on this previous work in order to reduce the background analysis.

Analysis of the measured level ice resistance required an estimate of pure ice resistance. This was derived from the results of the towed trials reported in Section 3, using:

$$R_{ice} = P + T - Row \qquad (4.1.1)$$

where:

R_{ice} = Pure ice resistance
P = Measured Towline pull
T = Measured propeller thrust (+) or Drag (-)
Row = clear-water resistance

The implication of this method is that total resistance, as overcome by the tow rope pull and propeller thrust, can be represented as the summation of ice and clear-water resistance components.

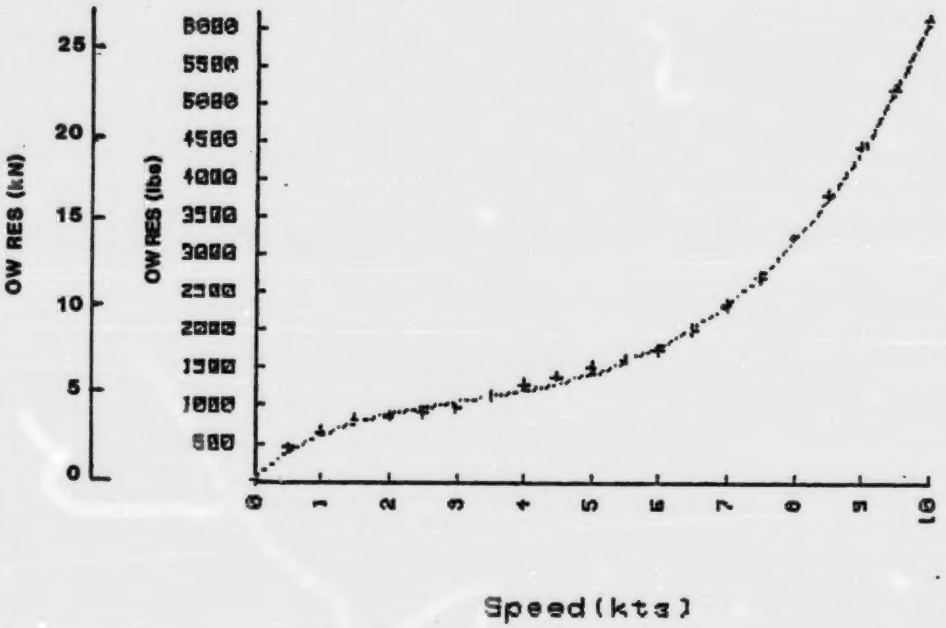
$$R_{tot} = R_{ice} + R_{ow} \qquad (4.1.2)$$

While this is intuitively reasonable, the determination of the clear-water term is not trivial. In this work the clear-water resistance estimate is based on open water model tests. Figure 4.1-1 snows these data and the curve fit used in the analysis. Table 4.1-1 gives the resistance values for the towed tests. There is some concern as to the validity of using these clear-water resistance values in the presence of an ice cover. However, viscous effects rather than wavemaking and form drag dominate in this speed range and therefore the values should be reasonable.

Previous analyses of full-scale trials data and model test data for level ice resistance have generally included three additive components; one which is speed dependent; another which is strength dependent; and a third which is independent of both others. The only common result of all this work is that the independent term has been identified as a function of the square of the ice thickness. Thus, the general form for ice resistance can be expressed as:

$$R_{ice} = A_0 h^2 + A_1 V^a h^b \sigma + A_2 V^c h^d \qquad (4.1.3)$$

where A_0, A_1, A_2, and a, b, c, and d are variable.



$$R_{ow} = 48 + 768.6V - 246V^2 + 42.2V^3 - 3.14V^4 + 0.122V^5$$

where:

R_{ow} = Open Water Resistance (lbs)

V = Ship Speed (knots) [0 to 10 knots]

$$R_{ow} = 214 + 3419V - 1094V^2 + 188V^3 - 14.0V^4 + 0.543V^5$$

where:

R_{ow} = Open Water Resistance (N)

Figure 4.1-1

CURVE FIT USED FOR OPEN WATER RESISTANCE

TABLE 4.1-1

RESISTANCE FROM TOWED TESTS

TEST	SPEED* (knots)	ICE THICKNESS (m)	R_{TOT} (N)	R_{OW} (N)	R_{ice} (N)
TOW-1	4.0	0.523	108612	5365	103247
TOW-2	5.0	0.475	165046	6361	158685
TOW-3	2.5	0.506	141911	4359	137552
TOW-4	1.8	0.506	102402	3879	98523
TOW-5	4.8	0.457	160963	6121	158842
TOW-6	3.7	0.358	64655	5142	59513
TOW-7	2.8	0.379	81709	4559	77150
TOW-8	6.3	0.320	142342	8598	133744
	6.8	0.320	148232	9862	138370
TOW-9	1.1	0.379	74311	2882	71429
TOW-9A	1.3	0.379	70028	3185	66843
TOW-10	4.9	0.379	112135	6236	105899
TOW-12	1.2	0.330	49949	3038	46911
TOW-13	7.6	0.381	166215	12486	153729
TOW-14	2.1	0.358	74365	4057	70308
TOW-15	7.4	0.424	168382	11752	156630
TOW-16	4.4	0.394	94369	5707	88662

* Speed: Rounded off values.

Two approaches have been followed in assessing the influence of the various parameters. The first is a pure number crunching approach which fitted the best values for all of the unknowns. The second is a dimensional analysis which permits a wider range of application in the results. The close relationship between non-dimensional expressions and the associated physical mechanisms of icebreaking, and their flexibility in examining parameters are the primary strengths of this approach. Lewis et al. [14] gives a functional expression for ice resistance as:

$$R_i = F(L,B,H,\nabla,A_x,h,\sigma_f,\sigma_c,E,\rho_i,\rho_w,(\rho_w-\rho_i),g,\mu,V) \quad (4.1.4)$$

where:

F = the function being sought
L = ship length at operating waterline
B = maximum beam at operating waterline
H = ship draft
∇ = ship displacement
A_x = midship area
h = ice thickness
σ_f = ice flexural strength
σ_c = ice crushing strength
E = ice elastic modulus
ρ_i = mass density of ice
ρ_w = mass density of water
g = acceleration of gravity
μ = hull-ice friction factor
V = ship speed

These variables can be represented by non-dimensional parameters which are derived according to similitude rules. The principal form of resistance equation used in this study is:

$$\frac{R_i}{\rho_w gBh^2} = R^* = C_0 + C_1\sigma' + C_2 V' \quad (4.1.5)$$

where:

σ' = a non-dimensional strength number
V' = a non-dimensional velocity number

Selection of the non-dimensional strength and velocity is based on the work of previous investigators, and includes variations on Froude Number, $(V/\sqrt{gL})$, and Cauchy Number, $(\rho V^2/E)$, as well as strength terms [Edwards 1972]. One anomoly in the numbers investigated, given in Table 4.1-2, is V*****. This form is a result of a 'best fit' analysis performed by Vance, [13], and is not a true non-dimensional number.

The first step in the analysis was the determination of simple correlations between non-dimensional resistance, R*, and each of the selected non-dimensional numbers. These are given in Table 4.1-3. Examination of these correlations and attempts at stepwise regression techniques showed the following trends:

TABLE 4.1-2

NON-DIMENSIONAL NUMBERS USED IN ANALYSIS

R^*	$R_{ice}/\rho_w g B h^2$
V^*	$V/\sqrt{gn}$
V^{**}	$V/\sqrt{gB}$
V^{***}	$V/\sqrt{gB} \cdot {}^{L}/h$
V^{****}	V^2/gh
V^{*****}	$V^2 L h^{1.35} B^{-.65}/gh$
V^{******}	V^2/gB
σ^*	$\rho_w V^2/\sigma$
σ^{**}	$\sigma/\rho_w gh$
V_{final}	$V^2/gB\ ({}^{L}/h)^3$

TABLE 4.1-3

SIMPLE CORRELATIONS FOR RESISTANCE DATA SET

CORRELATION OF:	WITH R^*
V^*	0.8710
V^{**}	0.8107
V^{***}	0.9103
V^{****}	0.9091
V^{*****}	0.9260
V^{******}	0.8379
σ^*	0.8006
σ^{**}	0.2507
${}^{L}/h$	0.4735
${}^{B}/h$	0.4735

- Correlation with value of ice strength was poor, as derived for each test and based on a temperature history. Strength terms did not improve the confidence of the estimates.

- Correlation with velocity squared terms was marginally better than corresponding linear fits.

- The best linear fit with velocity was obtained using the form postulated by Lewis et.al., [14], represented by V***.

Following an inspection of these results, 15 different forms were postulated for the resistance equation with the aim of developing meaningful physical understanding. As a reasonable limitation, only one non-dimensional velocity or strength number was used in each form, with possible combined powers representing combinations of viscous and non-viscous effects. Table 4.1-4 gives the results of curve fits for these forms. The details of each analysis and individual plots of all fits are found in Appendix B.

Each of the forms has been assessed, with emphasis on the degree of increased accuracy (or goodness of fit) as represented by correlations and/or standard error. The results are:

MODEL A: $Ri/\rho_w g\,Bh^2 = Co + C_1\,V/\sqrt{gh}$ (4.1.6)

This is the most commonly used simple form for resistance and it gives a baseline for comparison. A reasonably good correlation of 0.87 was noted.

MODEL E: $Ri/\rho_w gBh^2 = Co + C_1\,V/\sqrt{gB}$ (4.1.7)

This model is more rigorous than Model A since the independent variables are separated. However it has a marginally lower correlation than Model A.

MODEL B: $Ri/\rho_w gBh^2 = Co + C_1\,V/\sqrt{gh} + C_2\,V^2/gh$ (4.1.8)

MODEL F: $Ri/\rho_w gBh^2 = Co + C_1\,V/\sqrt{gB} + C_2\,V^2/gB$ (4.1.9)

These two models are modifications of A&E where a second order term was added to investigate a posible combination of viscous and non-viscous effects. The negative coefficients resulting from the regression make these unacceptable.

$$\text{MODEL C:}\quad Ri/\rho_w gBh^2 = Co + C_1\, V^2/gh \qquad (4.1.10)$$

$$\text{MODEL G:}\quad Ri/\rho_w gBh^2 = Co + C_1\, V^2/gB \qquad (4.1.11)$$

These models show significantly better correlation than their first order counterparts. In the case of Model C, improved correlation and lower standard error may be attributed to the h^{-1} term.

$$\text{MODEL D:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, \sigma/\rho_w gh + V/\sqrt{gh} \qquad (4.1.12)$$

$$\text{MODEL H:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, \sigma/\rho_w gh + V/\sqrt{gB} \qquad (4.1.13)$$

The addition of the velocity independent strength term to Models A and B results in unacceptable negative coefficients.

$$\text{MODEL I:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, V/\sqrt{gB}\; {}^{L}/h \qquad (4.1.14)$$

This model was first proposed by Lewis et al., [14] and combines the more stringent Breadth Froude Number with an aspect ratio containing the h^{-1} term. It is observed to improve correlation in Model C. Significantly higher correlation and lower standard error than for Model E or any of the other linear velocity models is observed.

$$\text{MODEL J:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, \sigma/\rho_w gh + C_2\, V/\sqrt{gh}\; {}^{L}/h \qquad (4.1.15)$$

By introducing a strength term into the form of Model I the correlation increases marginally, but the standard error also increases, which is an anomaly. This form may be useful for estimating strength effects, but there is no real confidence in the result.

$$\text{MODEL K:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, \rho_w V^2/\sigma \qquad (4.1.16)$$

This form utilizes a Cauchy Number, reflecting strength as a parameter. It results in a much lower correlation than any other V^2 model and reflects that there is little variation of strength in this data set.

$$\text{MODEL L:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, [V/\sqrt{gB}]^{C_2}\, [{}^{L}/h]^{C_3} \qquad (4.1.17)$$

$$\text{MODEL M:}\quad Ri/\rho_w g\, Bh^2 = Co + C_1\, [V/\sqrt{gh}]^{C_2}\, [{}^{B}/h]^{C_3} \qquad (4.1.18)$$

These two forms represent a departure from the use of fixed non-dimensional numbers, but avoid the mixed units of the pure regression approach using only important variables. The first form is analagous to that of Lewis et al., [14], (Model I), while the second is similar to that used by LeCourt, [11], in early model tests of the WTGB, (then WYTM). Both regressions confirm a squared velocity term behavior, while ship ice aspect ratios behave differently. Correlations are not meaningful in this context. However the standard error for these fits are much lower than for any of the simple models examined.

MODEL N: $Ri/\rho_w g\, Bh^2 = Co + C_1\, V^2/gh\, L\, h^{1.35} B^{-.65}$ (4.1.19)

This model is not dimensionless and resulted from a straight regression performed by Vance [13] in analyzing a number of different trials data sets. The correlation and standard error values are better than any of the simple models examined, but not as good as the more complex Models L and M. The velocity squared term again dominates, and as with both Models I and L, both L and B appear as ship parameters.

MODEL O: $Ri/\rho_w s\, Bh^2 = Co + C_1\, (V/\sqrt{gB})^{C_2}$ (4.1.20)

This model attempted to investigate the behavior of the data set with velocity, and it confirmed a dominant velocity squared relationship. The model does not have a very good standard error value, indicating that an additional term, such as thickness, is required in the velocity term.

After examining the results of this analysis the following observations may be stated:

- The resistance of the MOBILE BAY exhibited a dependence on the velocity squared, rather than the more general linear dependence which has often been postulated. The confidence in this trend is high, but the improvement in the accuracy of resistance estimates caused by this term alone is small, as exhibited by Models A and C or B and G.
- The range of thickness variation in these tests is small, ($\approx$ 20% of the mean), making it difficult to determine a thickness fraction in the velocity term.
- No useful correlation with ice strength was possible.
- A single velocity component is preferred.
- Since only one ship was tested, no conclusions can be formed regarding ship parameters, including friction.

Based on these observations, the following conclusions were reached:

1) The preferred form for pure ice resistance of the MOBILE BAY, and by inference, other conventional icebreakers is:

$$\frac{Ri}{\rho_w g\, Bh^2} = Co + C_1\, V^2/gB\, (L/h)^{\alpha} \tag{4.1.21}$$

This form includes an unknown exponent α, which is expected to be a constant. The variation of thickness in the data set is small, but both models L and M give a value of $\alpha = 3$ for this data. The best fit of the current data to this equation yields:

TABLE 4.1-4

SUMMARY OF FITTED RESISTANCE EQUATIONS

EQN	R*=	Co	C_1	C_2	C_3	r	S.E.(1)
A	$Co + C_1 V*$	2.153	4.3268	-	-	0.8710	22.5
B	$Co + C_1 V* + C_2 V***$	4.892	2.078	2.778	-	0.9133	19.3
C	$Co + C_1 V****$	3.945	1.913	-	-	0.9091	19.1
D	$Co + C_1 \sigma** + C_2 V*$	-0.065	0.0180	4.258	-	0.8909	21.5
E	$Co + C_1 V**$	2.270	21.693	-	-	0.8107	26.8
F	$Co + C_1 V** + C_2 V******$	4.376	-4.361	60.34	-	0.8387	25.8
G	$Co + C_1 V******$	3.999	50.713	-	-	0.8380	25.0
H	$Co + C_1 \sigma** + C_2 V**$	-1.286	0.0275	22.020	-	0.8595	24.2
I	$Co + C_1 V***$	2.231	0.2160	-	-	0.9103	19.0
J	$Co + C_1 \sigma** + C_2 V***$	1.1299	0.0093	0.2120	-	0.9153	19.1
K	$Co + C_1 \sigma*$	4.061	225.91	-	-	0.8006	27.5
L	$Co + C_1 V**C^{2}\ L/H\ C^{3}$	4.382	$8.8E^{-6}$	2.111	3.315	N/A	13.5
M	$Co + C_1 V*C^{2}\ B/H\ C^{3}$	4.382	$8.2E^{-4}$	2.112	2.259	N/A	13.5
N	$Co + C_1 V*****$	3.968	0.3035	-	-	0.9260	17.3
O	$Co + C_1 V**C^{2}$	3.996	50.491	1.996	-	N/A	25.9

NOTES: (1) Standard error as a percent of the mean of R*

$$\frac{R}{\rho_w g\ B h^2} = Co + C^1(V^2/gB)(L/h)^3 \qquad (4.1.22)$$

$Co = 4.2541$
$C_1 = 3.963 \times 10^{-5}$; with the degree of
regression, $r = 0.9610$ and
$SE = 12.7\%$

Figure 4.1-2 shows the regression line.

2) The difference in standard error and correlation is quite small between the best linear fit, (Eqn 4.1.14), and the chosen form. Therefore to assess the sensitivity of propulsion parameter derivations in Section 4.2 to the differences in resistance estimates, both linear and non-linear forms should be utilized.

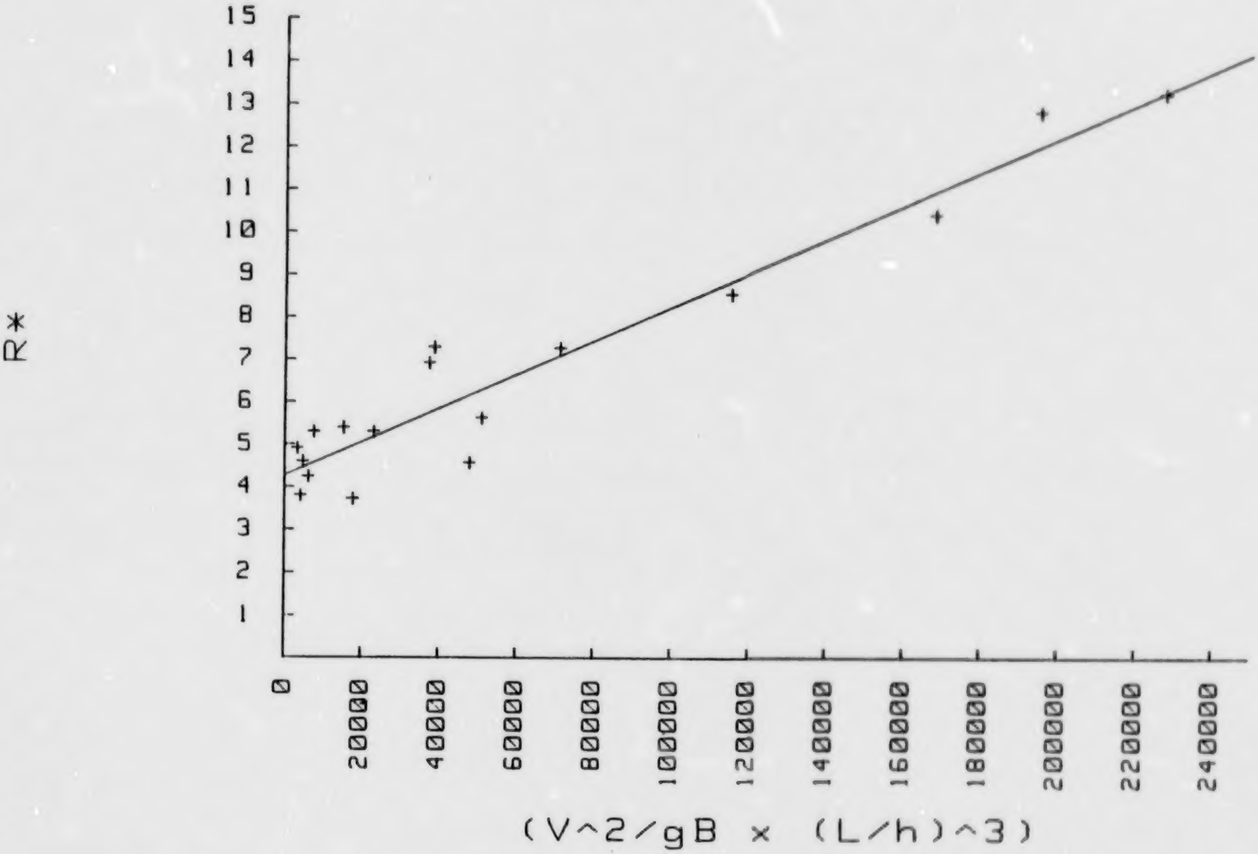


Figure 4.1-2

REGRESSION LINE FOR FINAL RESISTANCE FORM

4.1.2 Comparison With Other Resistance Estimates

The 140' WTGB, (formerly WYTM), is one of the most extensively tested designs of the U.S. Coast Guard's operational fleet. In addition to the model and full-scale resistance and propulsion tests in ice listed in Table 4.1-5, the vessels have undergone full-scale and model tests in open water for performance and maneuvering.

The resistance of the MOBILE BAY under tow gives the first opportunity to evaluate the suitability of model tests for determining resistance and the suitability of past procedures for deriving resistance estimates from full-scale trials. In examining these questions, a comparison of both raw data and empirical prediction equations has been undertaken. Figure 4.1-3 shows the raw data from the towed tests of MOBILE BAY:

KATMAI BAY TRIALS, 1979, [7]:

Over a period of 3 months in 1979, trials of the lead ship of this class, KATMAI BAY, were performed. The results were reported by Vance in 1980, [7]. The extensive trials included strength and friction studies as well as propulsion tests, with and without the installed bubbler operating. There were 16 data points with bubblers, in thicknesses between 28 cm and 51 cm (11" and 20"). Table 4.1-6 gives resistance estimates derived by Vance. This assumed a value of thrust deduction, (t) based on the form:

$$R = T(1 - t) \qquad (4.1.23)$$

A value of t equal to 0.20 was used, as a result of open water self-propelled tests, [12]. Figure 4.1-4 shows these estimates superimposed on those for MOBILE BAY. The trends are very similar, both with speed and thickness. The slope with speed appears somewhat flatter; but as discussed later, this may result from assuming a constant when it may vary with speed. Resistance rises more quickly with thickness in Vance's results, but this effect may be caused by higher strengths during the KATMAI BAY trials.

CRREL MODEL TESTS, 1984 [9]:

Resistance tests in level ice were performed at CRREL on two models of the 140' WTGB, at scales of 1:24 and 1:10. Tables 4.1-7 and 4.1-8 give the scaled up results for these two models. The tests were limited in scope since there was only one target ice thickness corresponding to 18 inches full scale. Figures 4.1-5 and 4.1-6 show the results of these tests superimposed on the MOBILE BAY results. Both models give estimates of resistance up to 300% higher than those for MOBILE BAY. Inspection of these plots shows that the predicted resistance is an average of about 150% high for both models. Much of this variation appears as an offset at zero speed, which is expectef for high friction and strength properties observed in the model study.

Nontheless, the offset is larger than that which is expected from these sources alone. Assuming an intercept for the MOBILE BAY data of 89,000N (20,000 lbs), and a strength term of the form:

$$\Delta R_{ice} = \Delta\sigma_f(0.01)\ Bh; \qquad (4.1.24)$$

then the strength difference would account for approximately 26,700N (6,000 lbs) on the 1:24 results and 17,800N (4,000 lbs) on the 1:10 results. If MOBILE BAY data is further modified to reflect a linear relationship between friction factor and the value of the intercept; then the expected value of the intercepts are 173,500N (39,000 lbs) and 142,300N (32,000 lbs) respectively. Although this is a very conservative assumption, the intercept values are still lower than those reported. The slope of the resistance trends with speed is also much higher than the MOBILE BAY data exhibits.

ARCTEC MODEL TESTS, 1975, [11]:

Model tests at 1:24 scale were conducted in saline ice at ARCTEC during the original design development of the 140' WTGB. These tests, like those at CRREL, utilized two models. In this case, friction rather than scale factor was varied. Tables 4.1-9 and 4.1-10 list the scaled up results from these tests. As seen in Figures 4.1-7 and 4.1-8, there is much better agreement in both magnitude and trends between the MOBILE BAY data and these tests than with the CRREL carbamide (urea) ice tests. The higher ice strength and lower model friction (Figure 4.1-7), make the data fall in the same range as full scale. However there seems to be a slightly lower slope to the trend with speed. The values for the higher friction model are higher than the full-scale results, and indicate some influence of friction on the variation of resistance with thickness, but no trend with velocity.

In summary, the correlations resulting from this analysis have been mixed. Full-scale and saline model test data showed good agreement, while urea ice tests proved unacceptable. The agreement with full-scale data is not unexpected, since the mean thrust deduction resulting from the analysis in subsequent sections is close to that assumed by Vance. The assumed fixed value of thrust deduction and the higher strength values may explain why trends vary as shown. The urea test results from CRREL suffer from a number of problems, including high values of strength and friction. Questions arise as to the agreement of the ARCTEC saline tests despite relatively high strength values, which supports the current analysis in indicating a low correlation between resistance and strength. The variation in results from the ARCTEC tests brings into question the proper modeling of full-scale friction values. Since, for any given vessel or class, the variation in friction at full scale is negligible there is no means to validate functional relationships derived in the basin. Therefore in order of importance, proper modelling of friction is first; followed by ice strength; and lastly by thickness and speed.

TABLE 4.1-5

RESISTANCE DATA AVAILABLE FOR 140' WTGB

STUDY	DATE	# (1) POINTS	$\bar{\sigma}_f$ (kPa)	μ	SCALE
MOBILE BAY FS	1986	17	455	(0.10)(2)	1:1
KATMAI BAY FS, [7]	1979	16	627	(0.15)(2)	1:1
CRREL CARBAMIDE	1984	14	827	.127 to .138	1:10
MODEL TESTS, [9]		15	1014	.134 to .162	1:24
ARCTEC SALINE	1975	27	938	.037	1:24
MODEL TESTS, [11]		41	1034	.280	1:24

NOTES:

(1) In the range of 23cm - 61 cm full scale
(2) Inferred from the condition of coating

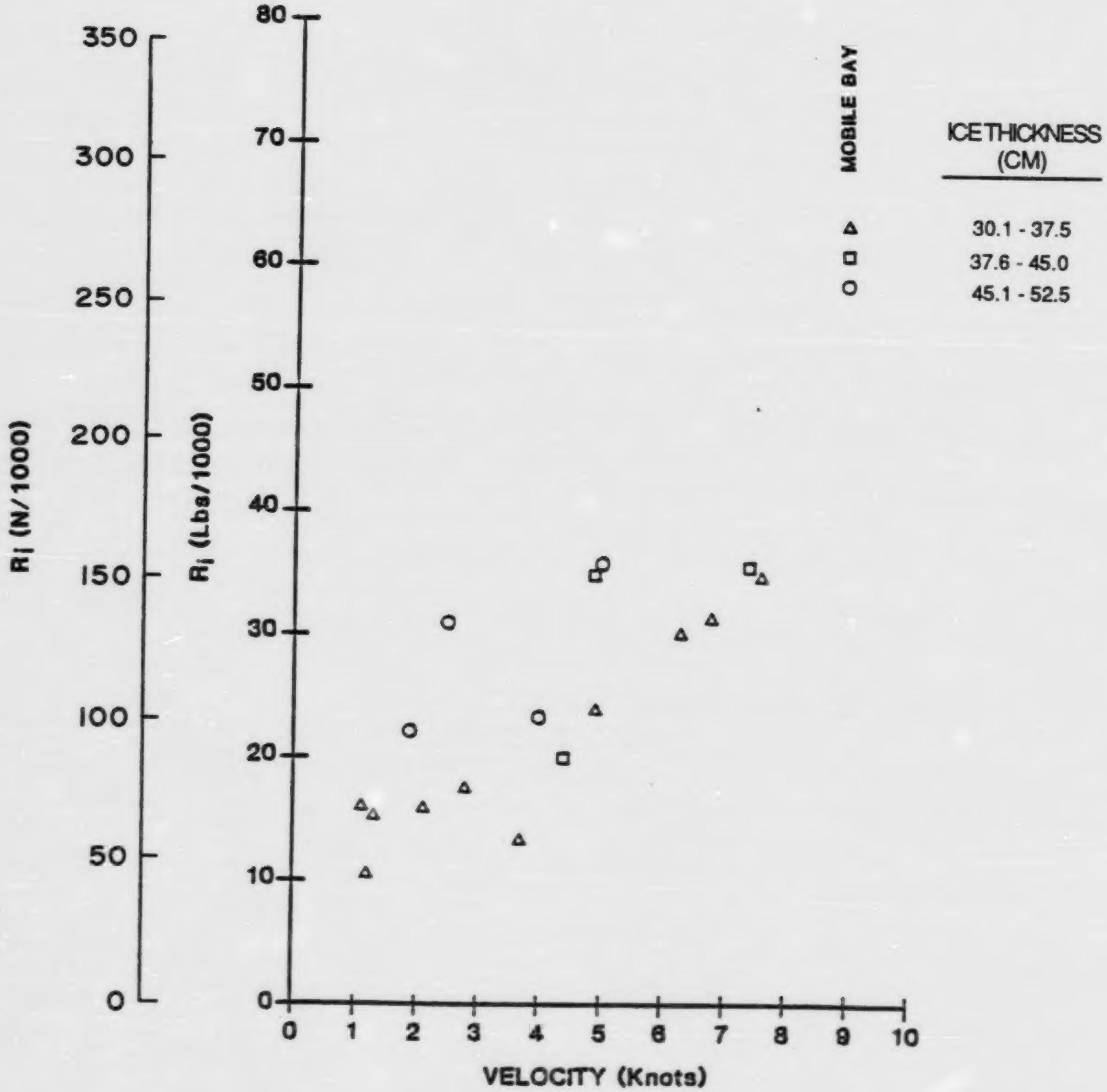


Figure 4.1-3

MEASURED RESISTANCE FOR MOBILE BAY FROM TOWED TRIALS

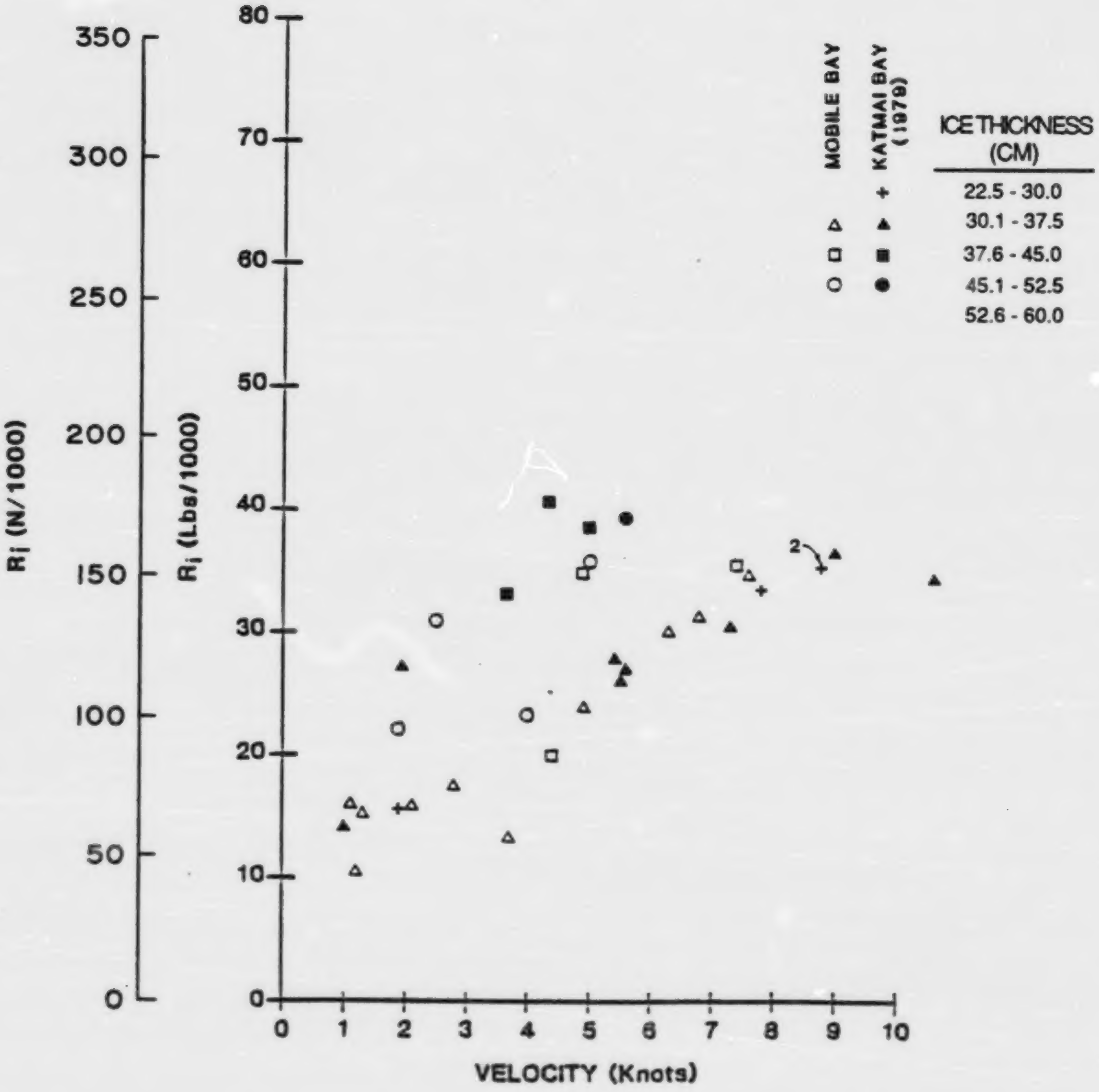


Figure 4.1-4

COMPARISON OF MOBILE BAY AND KATMAI BAY TEST DATA

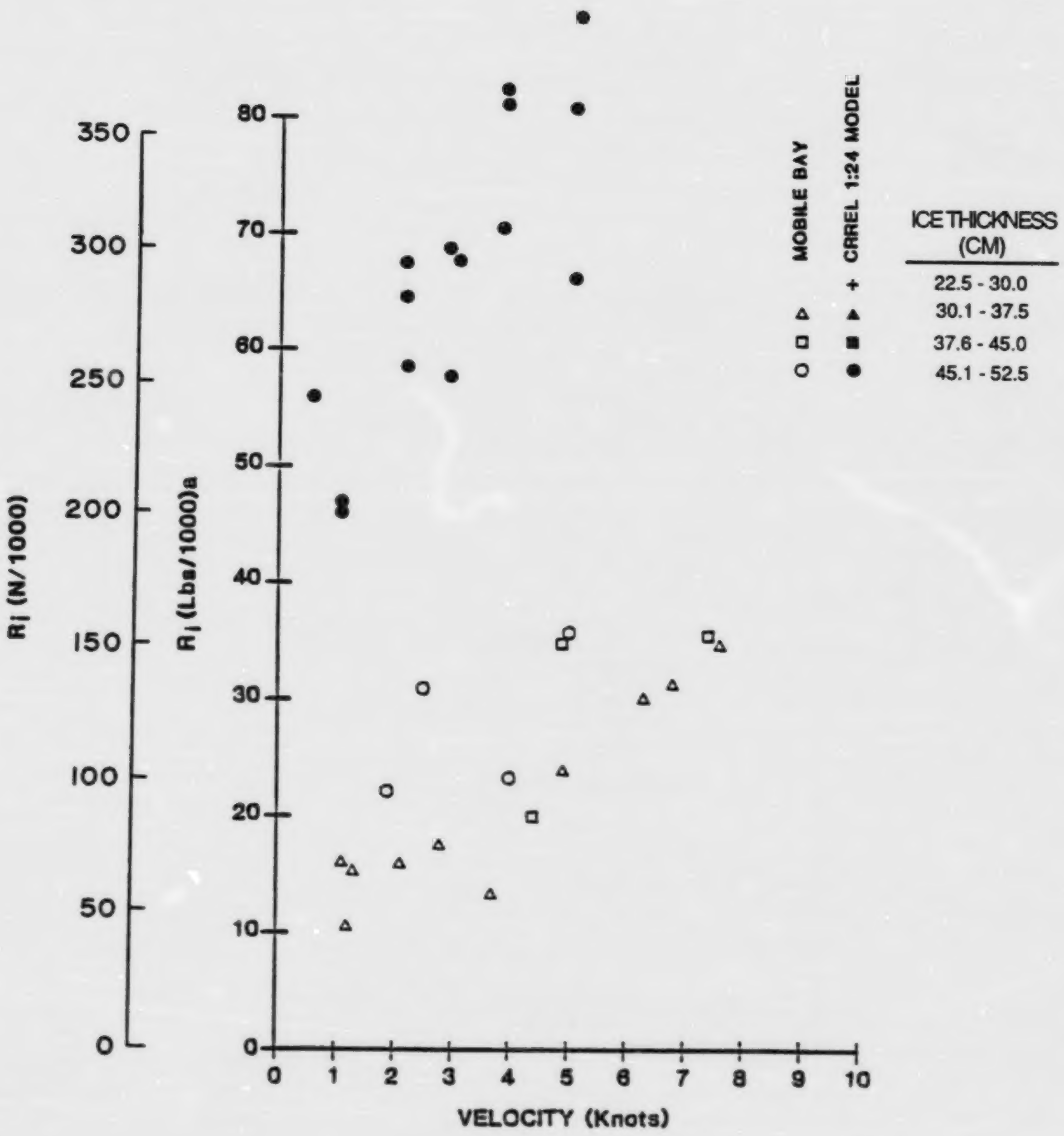


Figure 4.1–5
COMPARISON OF MOBILE BAY DATA WITH CRREL 1:24 SCALE MODEL

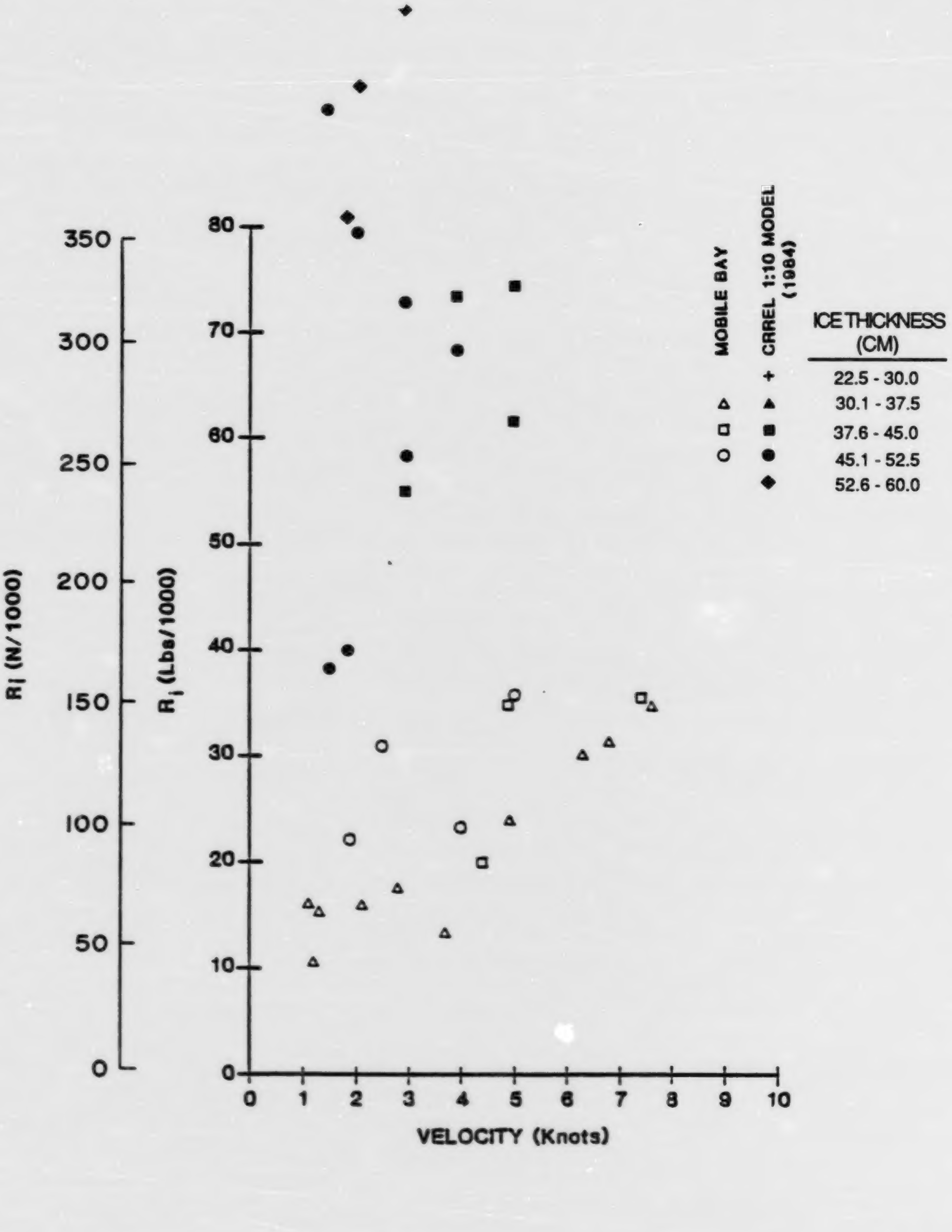


Figure 4.1–6

COMPARISON OF MOBILE BAY DATA WITH CRREL 1:10 SCALE MODEL

TABLE 4.1-6

REISTANCE ESTIMATES FROM KATMAI BAY TRIALS

(Vance, 1980)

RUN #	V (knots)	h (m)	R (N)	R*
1000	1.9	0.305	68422	7.21
1010	5.6	0.381	119331	8.05
1020	7.8	0.279	148027	18.56
1030	8.8	0.279	157039	19.69
1100	0.98	0.356	62875	4.87
1110	5.4	0.368	123219	8.89
1120	10.59	0.356	152880	11.83
1130	8.99	0.381	162572	10.96
1200	5.48	0.381	115657	7.80
1210	7.28	0.330	135536	12.17
1220	8.78	0.279	156919	19.64
1300	1.94	0.381	121004	8.16
1310	3.64	0.407	146790	8.70
1320	5.01	0.419	170468	9.47
1330	4.35	0.407	179778	10.65
1331	5.58	0.495	174342	12.58

$\bar{\sigma}_f$ = 627 kPa
μ = 0.150

TABLE 4.1-7

RESISTANCE ESTIMATES FROM CRREL 1:24 SCALE MODEL TESTS
(Tatinclaux, 1984)

TEST #	σ_f (kPa)	E (MPa)	V (knots)	h (m)	Ri (N)	R*
201	792	624	1.05	0.521	248818	8.97
202	912	624	2.19	0.516	299968	11.02
203	912	624	3.05	0.508	301347	11.37
204	912	624	3.90	0.536	360789	12.44
205	1008	624	5.04	0.521	359410	12.97
206	936	744	2.95	0.470	255731	11.29
207	1008	744	2.19	0.470	259881	11.48
208	1080	744	1.05	0.470	207352	9.16
209	1248	744	5.14	0.506	393968	15.04
210	1440	744	3.90	0.503	366318	14.12
211	912	648	3.81	0.488	313789	12.94
212	912	648	5.04	0.483	293056	12.33
213	960	648	2.95	0.501	304114	11.92
214	1080	648	2.19	0.495	287527	11.50
215	1080	648	1.05	0.498	204586	8.10

NOTE: All values scaled directly to prototype

μ = 0.134/0.162

$\bar{\sigma}_f$ = 1014 kPa

TABLE 4.1-8

RESISTANCE ESTIMATES FROM CRREL 1:10 SCALE MODEL TESTS*
(Tatinclaux, 1984)

RUN #	σ_f (kPa)	E (MPa)	V (knots)	h (m)	R (N)	R*
101	352	705	1.57	0.468	170050	6.58
102	315	705	1.94	0.462	178319	7.11
103	742	1586	1.94	0.565	361238	9.62
104	742	1586	3.03	0.577	460508	11.75
105	723	1326	3.03	0.464	260130	10.27
106	770	1326	4.00	0.463	304252	12.04
107	816	1001	3.03	0.456	244504	9.97
108	816	1001	5.09	0.456	275757	11.58
109	909	1539	4.00	0.453	327231	13.57
110	816	1539	5.09	0.455	330910	13.59
111	890	1428	3.03	0.478	324473	12.08
112	937	1428	2.12	0.507	353889	11.68
113	872	2022	2.12	0.511	414554	13.46
114	1001	2022	1.57	0.511	405364	13.19

NOTE: All values scaled direction to prototype

$\mu = 0.127/0.138$

$\bar{\sigma}_f = 827$ kPa

*Scale 1:9.273

TABLE 4.1-9

RESISTANCE ESTIMATES FROM ARCTEC MODEL TESTS: LOW FRICTION, 1:24 SCALE
(LeCourt, 1975)

TEST #	σ_f (kPa)	E (MPa)	V (knots)	h (m)	R (N)	R*
3	1134	866	0.6	0.244	16013	2.88
4	1134	866	7.1	0.241	80067	15.20
8	1016	1360	4.1	0.231	40923	8.32
9	1016	1360	1.9	0.244	36475	6.77
10	1016	1360	2.4	0.287	94301	12.47
11	1016	1360	5.1	0.318	73840	8.06
12	1016	1360	5.9	0.302	79177	8.41
13	1016	1360	6.9	0.229	54268	11.48
14	1016	1360	8.6	0.259	93412	15.20
15	772	393	3.4	0.467	101418	5.14
16	772	393	5.5	0.437	118322	6.81
17	772	393	0.7	0.442	47150	2.65
18	772	393	7.1	0.460	129887	6.68
19	772	393	4.6	0.437	96970	5.56
20	772	393	6.3	0.432	120101	7.04
21	772	393	7.6	0.470	128108	6.42
22	965	254	6.1	0.498	107646	4.78
23	965	254	6.0	0.523	144121	5.71
24	965	254	7.5	0.536	168141	6.38
25	965	254	2.4	0.498	95191	4.25
26	965	254	5.1	0.498	128108	5.70
27	965	254	6.9	0.500	137894	6.07
28	965	254	8.7	0.475	156576	7.58
36	941	289	4.1	0.597	153907	4.72
37	941	289	6.2	0.591	269560	5.67
38	941	289	7.4	0.605	201058	6.02
39	941	289	2.5	0.597	128108	3.94

NOTE: All values scaled directly to prototype

$\mu = 0.037$

$\overline{\sigma_f}$ = 938 kPA

TABLE 4.1-10

RESISTANCE ESTIMATES FROM ARCTEC MODEL TESTS: HIGH FRICTION, 1:24 SCALE
(LeCourt, 1975)

TEST #	σ_f (kPa)	E (MPa)	V (knots)	h (m)	Ri (N)	R*
1	885	1148	3.4	0.310	96970	11.07
2	885	1148	5.3	0.366	131666	10.86
3	885	1148	0.6	0.376	73840	5.77
4	885	1148	7.1	0.356	153907	13.35
5	885	1148	4.5	0.335	120101	11.63
6	885	1148	6.4	0.295	131666	16.59
7	885	1148	7.7	0.244	106756	19.86
9	1294	762	5.9	0.239	137894	26.78
10	1294	762	7.4	0.277	188603	26.69
11	1294	762	2.3	0.330	140563	14.23
12	1294	762	5.1	0.279	141452	19.68
13	1294	762	6.8	0.259	161024	26.26
14	1294	762	8.6	0.229	169031	36.48
15	1016	357	3.3	0.493	245540	11.01
16	1016	357	5.5	0.523	326497	12.96
17	1016	357	0.6	0.523	160135	6.40
18	1016	357	7.1	0.518	322939	13.18
19	1016	357	4.5	0.478	227747	10.93
20	1016	357	6.2	0.473	261554	12.82
21	1016	357	7.5	0.478	282015	13.55
22	842	146	4.0	0.447	210844	11.46
23	842	146	6.0	0.452	241092	12.96
24	842	146	7.3	0.445	271340	14.91
25	842	146	2.3	0.452	181486	9.77
26	842	146	5.0	0.455	241982	12.89
27	842	146	6.8	0.460	234864	12.12
28	842	146	8.5	0.475	301587	14.62
29	864	242	3.3	0.536	220630	8.43
30	864	242	5.3	0.592	315822	9.85
31	864	242	0.6	0.605	141452	9.28
32	864	242	6.9	0.600	326497	9.95
33	864	242	4.5	0.595	268671	8.31
34	864	242	6.2	0.595	335394	10.37
35	864	242	7.4	0.610	348738	10.28
36	1068	360	4.1	0.605	346069	10.45
37	1068	360	6.2	0.592	358524	11.26
38	1068	360	8.8	0.595	405675	12.54
39	1068	360	2.3	0.592	262443	8.26
40	1068	360	8.5	0.589	412792	13.08
41	1068	360	5.7	0.574	330056	11.0
42	1068	360	6.8	0.584	415461	13.27

$\bar{\sigma}_f$ = 1034 kPa
μ = 0.280

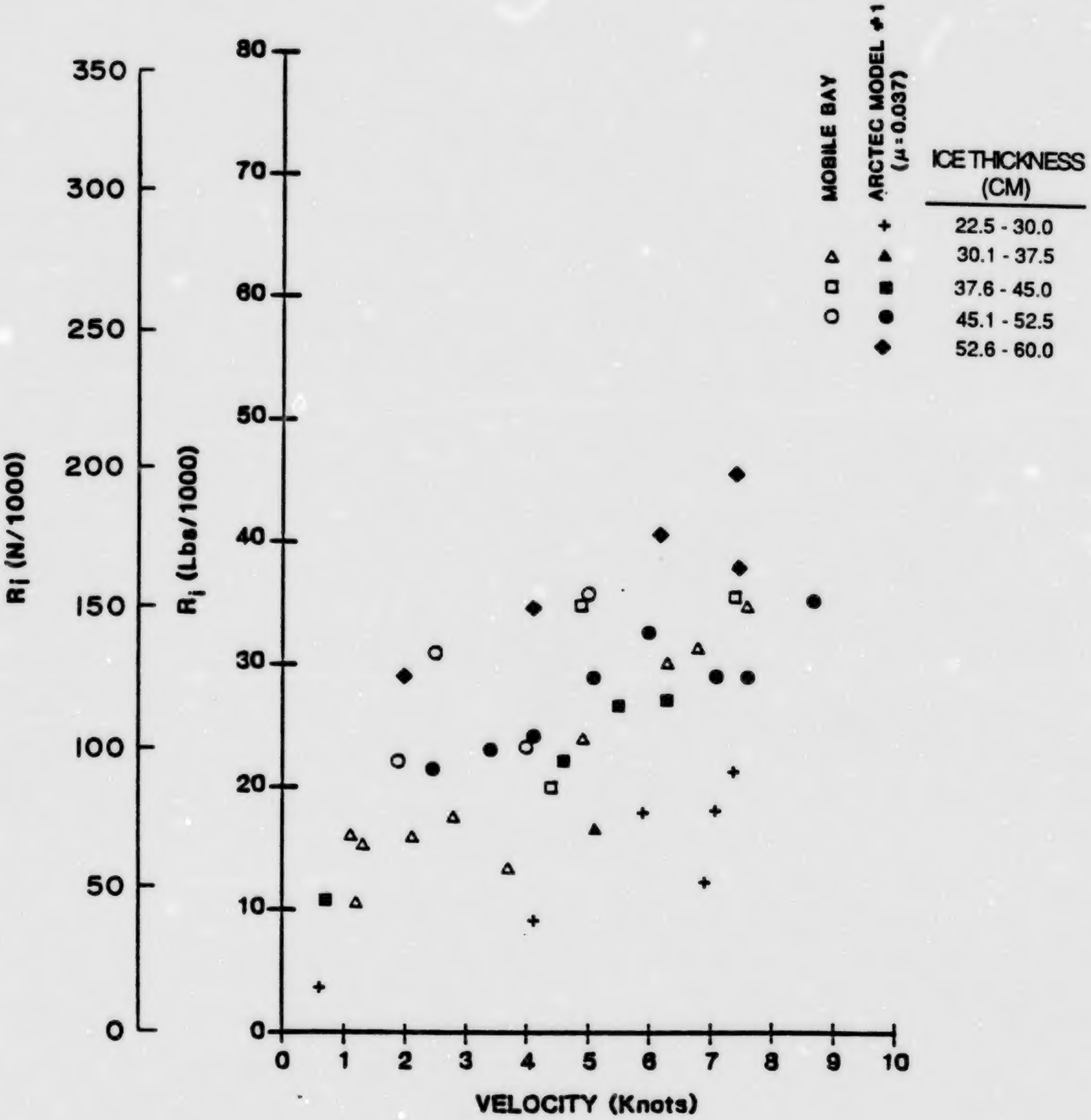


Figure 4.1-7

COMPARISON OF MOBILE BAY DATA WITH ARCTEC LOW FRICTION MODEL

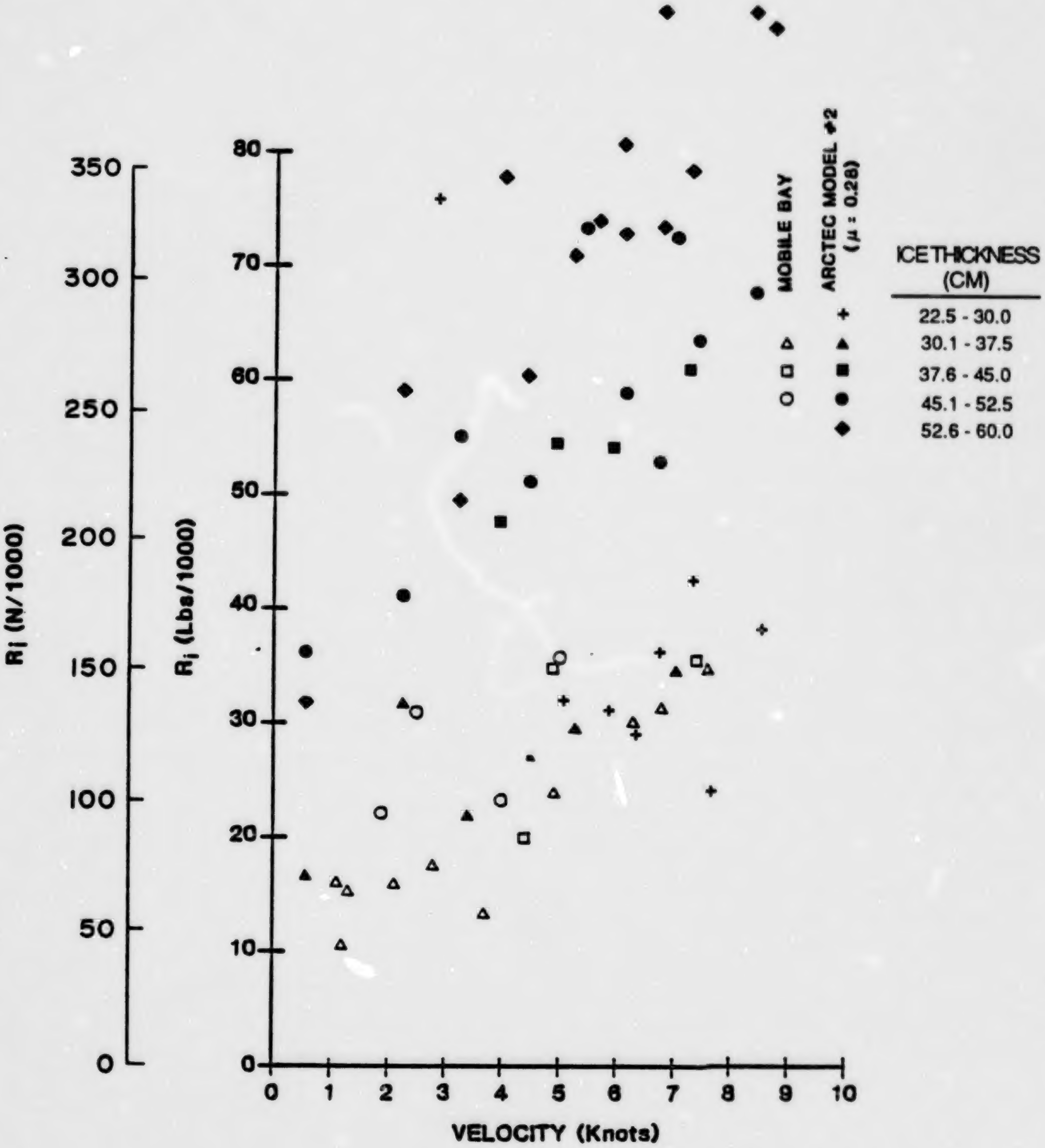


Figure 4.1-8

COMPARISON OF MOBILE BAY DATA WITH ARCTEC HIGH FRICTION MODEL

The final comparisons made were between the fitted forms of EQN 4.1.14, (the linear fit), EQN 4.1.22, (the non-linear fit), and empirical predictors derived from the model and full-scale studies. A basis thickness of 40.6cm (16") was chosen for this comparison, and therefore the fits for the CRREL tests are strictly invalid, since all tests were conducted at one thickness, 85.8cm (18"). Table 4.1-11 gives the forms used and parameters for the comparison. Since all forms allow for variable ice strength except the current data, the mean for the current tests was used. The equation derived by LeCourt, [11], for the saline test data included a friction variation term for which the friction factor, μ, was set at 0.10. Figure 4.1-9 shows the predicted ice resistance in 40.6cm (16 in) of ice at various speeds.

The trends in these predictions are quite clear. All of the fits are linear with velocity, with the exception of the current non-linear model. Each linear fit approaches either the slope of the lower portion of the non-linear fit or the upper portion. The reasons for this vary with each analysis, as do the expectations and results of this comparison.

Lewis et al., [13]: $R_{ice}/\rho_w g\, Bh^2 = 3.8989 + 0.0123\ \sigma/\rho_w gh + 0.223\left(\frac{V}{\sqrt{gB}}\right)\left(\frac{L}{n}\right)$

This form was developed through analysis of full-scale data for four different ships, and is a useful estimator in early stages of design. These ships ranged in size from the MANHATTAN to the KATMAI BAY. The slope of the prediction curve in Figure 4.1-9(A), closely matches the linear fit to the current data, (D). This slope is coincident with what would be the mean for the upper 2/3 of the curvilinear fit. The major problem is the elevated value of the intercept. Three separate factors may affect this result: For at least two of the ships in the data base, no low friction coating was employed. Most of the trials data used was obtained with significant snow cover present. These first two factors combine to lend a higher friction basis to the data, with an expected elevation to the intercept. Also, a relatively small portion of the data, ($\sim$ 15%), was taken at speeds of less than 2 knots, and most of the data, (85%), was in thicknesses greater than 45.8cm (18 in). This last factor tends to reduce the confidence in predictions near the intercept for these thicknesses. On the other hand, the intercept is fairly close to the other three fits for the 140-foot WTGB form. It is possible, therefore, that it is the combination of slope and intercept which is in error, rather than one or the other. Reanalysis of the data might indicate a higher dependence of slope or intercept for the ships with either friction or hull form than is currently included. As it now stands, the Lewis resistance form overpredicts by as much as 40%.

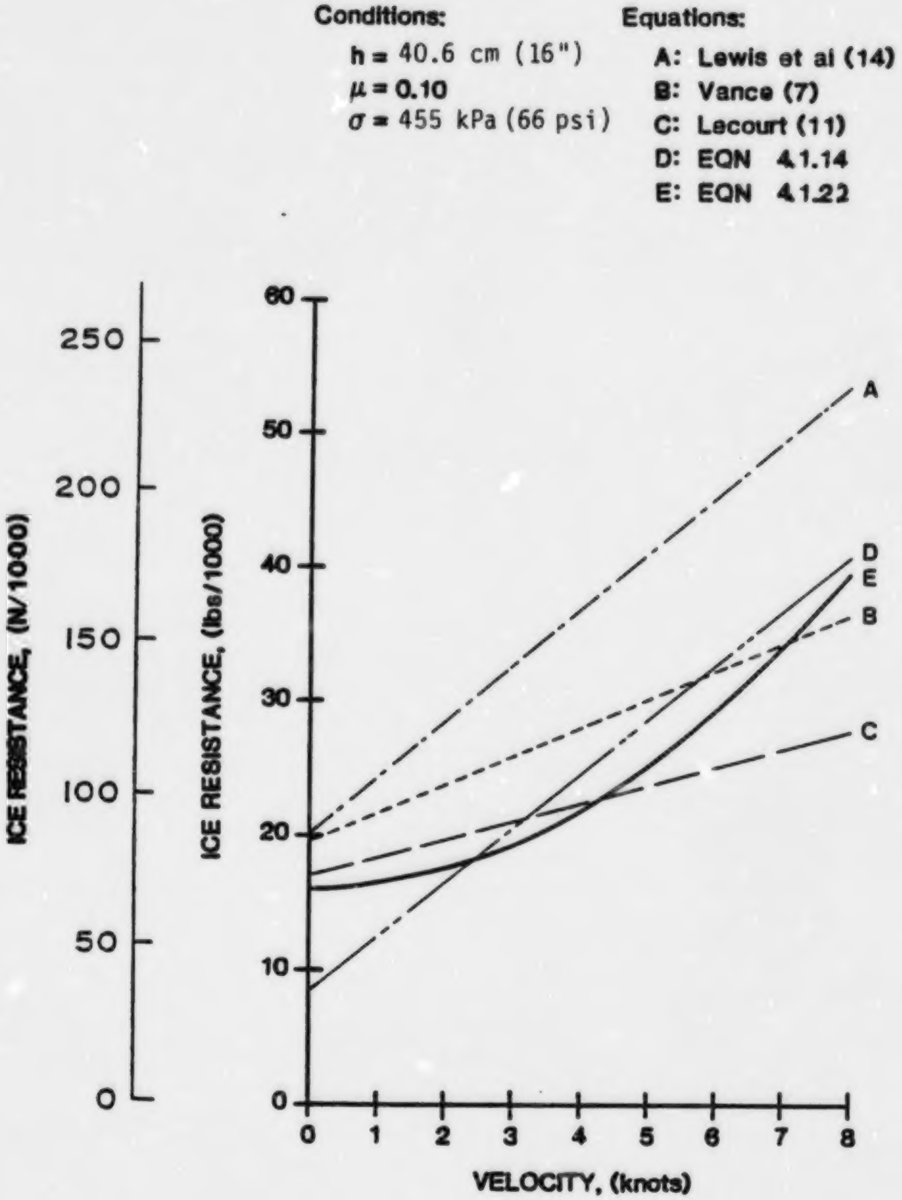


Figure 4.1-9

RESISTANCE ESTIMATES USING EMPIRICAL EQUATIONS

TABLE 4.1-11

COMPARISON OF RESISTANCE ESTIMATES FOR 140' WTGB (BAY CLASS)

Based on:
$h = 0.4065\text{m}$
$\rho_w = 1000\ \text{kg/m}^3$
$(\rho_w - \rho_i) = 92.8\ \text{kg/m}^3$
$B = 10.42\text{m}$
$L = 39.63\text{m}$
$\sigma = 455\ \text{kPa}$

ICE RESISTANCE, R_{ice} (N), For EQN;

VELOCITY (knots)	A	B	C	D	E
0	89053	86967	75,726	37436	71380
2	126316	105618	87629	73528	77826
4	163583	124269	99537	109617	97166
6	200836	142920	111440	145696	129384
8	283090	161572	123344	181776	174494

EQUATIONS:

A: General form of Lewis et al., [14]

$$R_{ice}/\rho gBh^2 = 3.899 + 0.0123\ \sigma/\rho gh + 0.223\ (V/\sqrt{gB})(L/h)$$

B: Vance Results from KATMAI BAY TRIALS, [7]

$$R_{ice}/\rho_w gBh^2 = 5.184 + 0.0188\ V\left(\frac{\sigma}{\rho gh^2}\right)\sqrt{h/g}$$

C: Lecourt Results from Model Tests, [11]

$$R_{ice}/\rho_w g\ Bh^2 = 4.513 + 0.012\ (\sigma/\rho_w gh)\ (V/\sqrt{gh}$$

D: Linear fit from current analysis, (EQN 4.1.14)

$$R_{ice}/\rho_w g\ Bh^2 = 2.231 + 0.2160\ (V/\sqrt{gB})\ (L/h)$$

E: Non-Linear fit from current analysis, (EQN 4.1.22)

$$R_{ice}/\rho_w g\ Bh^2 = 4.254 + 3.963 \times 10^{-5}\ (V/\sqrt{gB})^2\ (L/h)^3$$

Vance from Full-Scale Trials, [7]:
$R_{ice} = 55.86\,(\rho_w - \rho_i) g B h^2 + 0.0188\,\sigma V B \sqrt{h/g}$

The results of the KATMAI BAY trials resulted in the equation above. In Figure 4.1-9, the linear prediction, (B), shows a relatively high intercept, but a slope closer to the lower portion of the curvilinear fit, (E). This results in agreement in the range of ultimate capability as observed in the self-propelled trials, approximately 6-7 knots in 40.6cm (16") of ice. The overprediction at lower speeds and the low slope may be introduced as an influence of strength. The low range of strength variation in the trials, from 580 to 640kPa (84 to 93 psi), makes this term questionable. The high quantities of snow during these tests, 10-12cm (4-5"), is a likely cause of the apparent increase in friction and therefore the intercept. The net result is that although predictions cross in the range of ultimate capability, the form derived by Vance overpredicts by 25% in the middle of the operating range.

LeCourt From Model Tests, [11]: $\frac{R_{ice}}{\rho_w g B h^2} = 4.513 + 0.012\,(\sigma / \rho_w g h)\,(V / \sqrt{gh})$

This equation is roughly the same form as that of Vance, [7]. A low slope to the linear prediction, (C), indicates a problem in the second term. The range of strengths for this test series was larger than in the full-scale tests, and between 690 and 1240kPa (100-180 psi), but still much higher than the value used in this analysis. Thus it again appears that the inclusion of the strength term in conjunction with velocity is detrimental. The intercept for this fit matches very well with the curvilinear fit, (E) from the current data. No snow in the basin and interpolation of the coefficients to reflect friction changes reinforce concerns voiced over the validity of the intercepts of Lewis [13], and Vance [7]. The model test line [11] is actually a fairly good agreement with the curve from the current data, (E), varying ± 15% over the range from 0 to 6 knots.

In summary, the comparison of the current results with other data sets and empirically derived predictions lead us to conclude:

1) Full-scale trials results match well when appropriate thrust deduction values are assumed. In the case of the KATMAI BAY trials, the 0.2 value of t was close.

2) There are significant questions regarding the validity of estimates obtained from model tests in urea ice. Tests in saline ice produced much better agreement. The critical parameters which must be properly modeled, in order of importance, are:

   - hull-ice friction
   - ice strength
   - thickness
   - speed

The importance of correct selection of target values is equally important. None of the model tests were conducted in the range of strengths experienced at full scale.

3) Empirically derived predictions are extremely sensitive to friction conditions.

4) The effect of strength is often overstated, especially when considering the variation in any particular data set.

4.2 ANALYSIS OF SELF-PROPULSION RESULTS

It is the objective of this section to appraise the trials self-propulsion results and thereby determine trends in propulsive coefficients for ships in level ice. By comparison with corresponding trends at model scale it has been possible to assess the strengths and weaknesses of current model testing techniques and performance analysis procedures.

The MOBILE BAY trials values of thrust, torque, RPM and ship velocity have first been expressed as non-dimensional parameters: K_T, K_Q and J_s. Note that J_s is the measured ship advance coefficient determined from the ship speed, V_s, and RPM in equation 4.3.2a. This reformulation assumes traditional open water methods and allows a comparison with earlier KATMAI BAY trials and with model tests. Overall efficiency (behind in ice) is derived from K_T, K_Q and V_A, propeller advance velocity.

Since V_A is not a measured quantity, it is usually estimated from the open water propeller curve and the measured K_T by means of the shaft thrust identity method. It is assumed in this method that the relationship between K_T and J_{Bi} (behind in ice) is the same as the curve which was derived for the model scale stock propeller in open water propeller tests. Hence V_A can be calculated from equation 4.2.3 once the propeller advance coefficient, J_{Bi}, has been derived using the measured K_T as input to the open water propeller curves. Wake fraction is defined in terms of this propeller advance velocity.

Full-scale towed resistance results are introduced from Section 4.1 and compared with thrust to give thrust deduction in level ice. Subsequently the thrust deduction and wake fraction estimates have been utilized to break down the overall efficiency in ice into hull, relative rotative and open-water components.

Several trends in propulsion performance have been identified by means of regression analysis techniques which allows investigation of the influence of different physical parameters. Details of the approaches which have been adopted in each of the analysis steps and pertinent results are provided in the following subsections.

4.2.1 Characteristics of MOBILE BAY in Level Ice

The thrust, torque, RPM and ship velocity data from the MOBILE BAY trials have been reduced into various dimensionless variables as follows:

$$K_T = \frac{T_i}{\rho n^2_{Bi} D^4} = \text{Thrust Coefficient} \qquad (4.2.1)$$

$$K_Q = \frac{Q_{Bi}}{\rho n^2_{Bi} D^5} = \text{Torque Coefficient} \qquad (4.2.2)$$

$$J_s = \frac{V_S}{n_{Bi} D} = \text{Ship Advance Coefficient} \qquad (4.2.3a)$$

$$J_{Bi} = \frac{V_A}{n_{Bi} D} = J_A = \text{Propeller Advance Coefficient} \qquad (4.2.3b)$$

where T_{Bi} is thrust, Q_{Bi} is torque, n_{Bi} is RPM/60, ρ is water mass density and D is propeller diameter. The subscript Bi refers to physical measurements of propeller characteristics behind the ship in ice.

Tables 4.2-1A and 4.2-1B presents the dimensionless parameters from the MOBILE BAY trials. Figure 4.2-1 compares the observed propeller performance data in level ice for the MOBILE BAY with West's [12] K_T and K_Q curves which define the open water characteristics of the 140' WTGB propeller as a function of J_s. Higher thrust and torque values are observed for the icebreaking condition. The corresponding mean lines reproduced from the KATMAI BAY trials in similar ice conditions are also shown. Given that certain difference do exist between the two test series, the data sets are in excellent agreement.

The principal characteristic of the trials K_T line is that it has been shifted upwards by a constant. The K_Q results tend to constant value as ice thickness increases, which corresponds to the bollard K_{Qo} value of the open-water propeller curve.

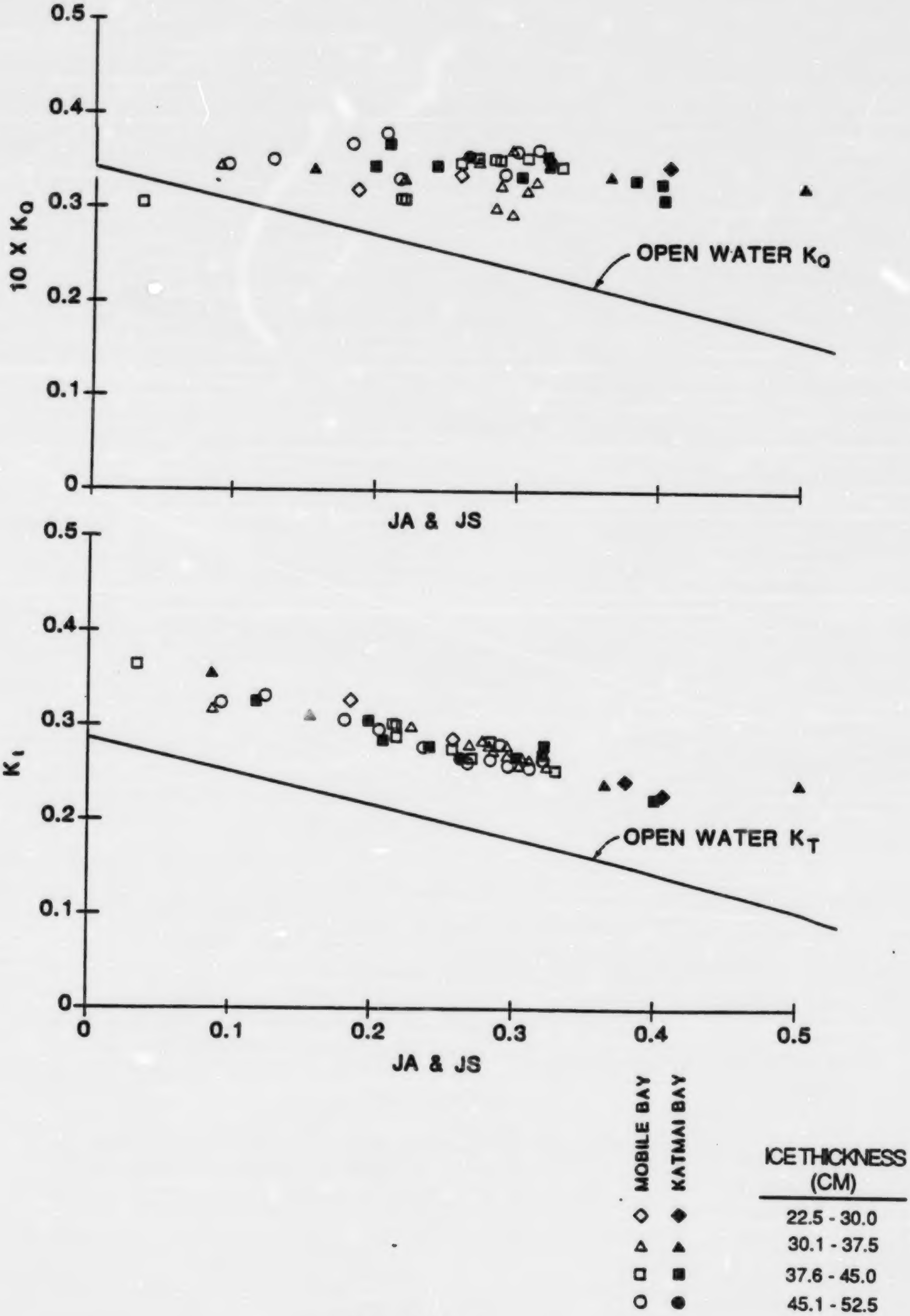


Figure 4.2-1
MOBILE BAY PROPELLER PERFORMANCE CURVES AND COMPARISON
TO OPEN WATER PREDICTIONS

TABLE 4.2-1A

MOBILE BAY TRIALS: DIMENSIONLESS PROPULSIVE COEFFICIENTS

TEST	‡h/D	J_s	K_T	10 K_Q	t1	W_t
1	0.1812	0.1823	0.3060	0.3690	0.3085**	1.389
2A	0.1812	0.1247	0.3266	0.3509	0.2173**	2.122
2B	0.1812	0.2368	0.2782	0.3830*	0.2348**	0.9213
3	0.1812	0.2049	0.2956	0.3808	0.2238**	1.181
4	0.1812	0.2688	0.2626	0.3791*	0.1274**	0.7506
5A	0.1859	0.3122	0.2592	0.3641	-0.1960**	0.7518
5B	0.1859	0.2896	0.2795	0.3383	-0.4778**	0.9504
5C	0.1859	0.3219	0.2638	0.3466	-0.0933**	0.8033
6A	0.1518	0.2180	0.3009	0.3109	0.1893	1.249
6B	0.1376	0.3116	0.2639	0.3292	0.3139	0.798
6C	0.1271	0.2865	0.2739	0.3254	0.3510	0.8888
7A	0.1329	0.2842	0.2790	0.2995	0.2631	0.9434
7B	0.1212	0.3064	0.2670	0.3187	0.3745	0.8253
7C	0.1518	0.0341	0.3620	0.3026	0.4940	8.732
8	0.1471	0.2857	0.2844	0.3508	0.2452	1.004
9A	0.1082	0.1856	0.3293	0.3176	0.4673	1.802
9B	0.1035	0.2586	0.2873	0.3366	0.4880	1.040
10A	0.1224	0.2956	0.2706	0.3440	0.3470	0.8571
10B	0.1518	0.2172	0.3007	0.3117	0.1294	1.246
10C	0.1518	0.3296	0.2542	0.3457	0.1557	0.7184
11	0.1376	0.2950	0.2797	0.3606	0.2735	0.9543
12	0.1224	0.3226	0.2588	0.3633*	0.3624	0.7564
13	0.1271	0.2277	0.2976	0.3315	0.2732	1.191
14	0.1271	0.2702	0.2798	0.3488	0.2968	0.9502
15A	0.1671	0.2846	0.2666	0.3506	0.0749	0.8081
15B	0.1471	0.2171	0.2905	0.3316	0.1431	1.095
16A	0.1471	0.2571	0.2767	0.3520	0.1874	0.9099
16B	0.1765	0.2971	0.2606	0.3635	0.0159	0.7539
16C	0.1718	0.0933	0.3231	0.3469	0.0974	2.372
17A	0.1565	0.3046	0.2571	0.3574	0.1246	0.7246
17B	0.1224	0.0880	0.3182	0.3449	0.4651	2.265
17C	0.1471	0.2706	0.2660	0.3524	0.2235	0.7913

NOTE: * Torque Overrange
‡ D = 2.6m (8.5 ft)

** Tests not included in thrust deduction analysis due to uncertainty in ice thickness data.

TABLE 4.2-1B

MOBILE BAY TRIALS: DIMENSIONLESS PROPULSIVE COEFFICIENTS

TEST	h/D	J_s	t2	η_{D1}	η_{D2}	η_{Rt}
1	0.1812	0.1823	0.3545**	0.1664	0.1553	0.9944
2A	0.1812	0.1245	0.1683**	0.1446	0.1683	1.126
2B	0.1812	0.2360	0.3549**	0.2095	0.1766	0.8700
3	0.1812	0.2049	0.2997**	0.1964	0.1772	0.9292
4	0.1312	0.2688	0.2796**	0.2585	0.2134	0.8331
5A	0.1859	0.3122	0.2053**	0.4230	0.3464	0.8574
5B	0.1859	0.2896	-0.2984**	0.5627	0.4944	0.9894
5C	0.1859	0.3219	0.1127**	0.4264	0.3460	0.9151
6A	0.1518	0.2180	0.2544	0.2722	0.2504	1.159
6B	0.1376	0.3116	0.3126	0.2729	0.2734	0.9640
6C	0.1271	0.2865	0.3496	0.2491	0.2497	1.009
7A	0.1329	0.2842	0.3019	0.3105	0.2941	1.116
7B	0.1212	0.3064	0.3035	0.2555	0.2845	1.006
7C	0.1518	0.0341	0.1773	0.0329	0.0534	1.492
8	0.1471	0.2857	0.3240	0.2783	0.2492	0.9704
9A	0.1082	0.1856	0.4683	0.1632	0.1629	1.256
9B	0.1035	0.2586	0.4130	0.1799	0.2062	1.021
10A	0.1224	0.2956	0.3147	0.2414	0.2533	0.9428
10B	0.1518	0.2172	0.1888	0.2903	0.2705	1.156
10C	0.1518	0.3296	0.2192	0.3256	0.3011	0.8876
11	0.1376	0.2990	0.3147	0.2647	0.2496	0.9291
12	0.1224	0.3236	0.2555	0.2338	0.2731	0.8579
13	0.1271	0.2277	0.3164	0.2364	0.2223	1.075
14	0.1271	0.2702	0.3267	0.2426	0.2323	0.9607
15A	0.1671	0.2846	0.2161	0.3186	0.2700	0.9133
15B	0.1471	0.2171	0.2031	0.2594	0.2412	1.049
16A	0.1471	0.2571	0.2773	0.2615	0.2325	0.9419
16B	0.1765	0.2971	0.1844	0.3337	0.2766	0.8631
16C	0.1718	0.0933	-0.2069	0.1249	0.1670	1.124
17A	0.1565	0.3096	0.2332	0.3053	0.2674	0.6673
17B	0.1224	0.0880	0.3373	0.0691	0.0857	1.111
17C	0.1471	0.2706	0.3081	0.2524	0.2249	0.9066

‡ NOTE: D = 2.6m (8.5 ft)

** Tests not included in thrust deduction analysis due to uncertainty in ice thickness measurements.

4.2.2 Thrust Deduction Fraction

Thrust deduction is a measure of the difference between the required thrust to drive a ship and the resistance at corresponding speeds and ice conditions. The thrust is normally measured in full-scale self-propulsion trials and in model tests. The resistance has previously been exclusively from model tests. The towed trials of MOBILE BAY have permitted a direct calculation of thrust deduction, where both thrust and resistance are extracted from full-scale data.

Thrust deduction in ice is defined as:

$$t = \frac{T_{Bi} - R}{T_{Bi}} = 1 - \frac{R}{T_{Bi}}$$

where T_{Bi} is thrust and R is total resistance. Two thrust deduction formulations based on different resistance regression equations have been assessed. Trends in t_1 are associated with the linear Form 1 (4.1.14) resistance regression equation and t_2 by the nonlinear Form 2 (4.1.17) equation respectively from Table 4.1-4 of Section 4.1. These two resistance forms were chosen because of their effectiveness in representing a large database of trials and model test results, as well as the present MOBILE BAY data. The 'best fit' equation (4.1.2.2) has not been used since it has not been tested against other vessels. Both of the selected resistance equations accurately represent the towed trials data. However small differences in R may significantly affect t, and therefore the duplication is helpful in assessing trends. Values of t_1 and t_2, for each trial run, are given in Tables 4.2-1A and 4.2-1B respectively.

Figure 4.2-2 shows t_1 plotted as a function of ice thickness. A linear regression line with negative slope provides a good fit to the data points. An analysis of residuals does not indicate any significant variation of t_1 with J_s. An analogous linear relationship is found in Figure 4.2-3 where the Form 2 resistance formulation is used in the calculation of t_2. The two regression equations are:

$$t_1 = 1.106 - 0.708\ h\text{, with h in feet} \qquad (4.2.4)$$
$$1.106 - 0.0232\ h\text{, with h in meters}$$

$$t_2 = 0.919 - 0.545\ h\text{, with h in feet} \qquad (4.2.5)$$
$$1.106 - 0.0179\ h\text{, with h in meters}$$

The trials t values significantly exceed the expected clear water value for small J_s and therefore a trend showing a maximum thrust deduction in the thinnest ice range has been postulated. Further trials in thin ice and at varied J_s are necessary to investigate this trend and verify whether or not it is merely a result of increased ice loads in the thicker ice overshadowing the hydrodynamic affects which give rise to thrust deduction in clear water.

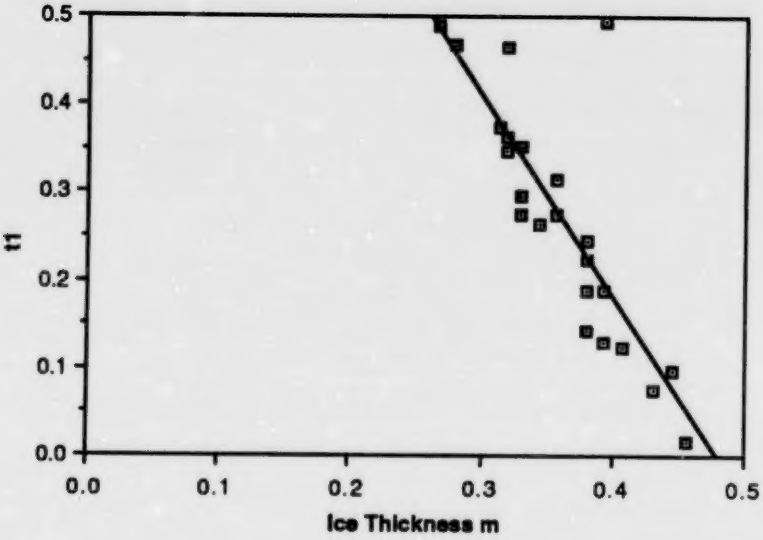


Fig. 4.2-2 THRUST DEDUCTION t1 VARIATION WITH ICE THICKNESS

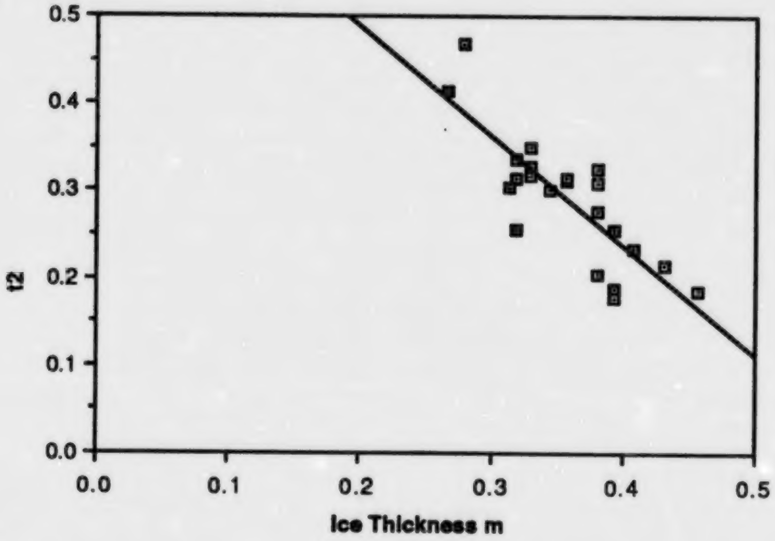


Fig. 4.2-3 THRUST DEDUCTION t2 VARIATION WITH ICE THICKNESS

At an ice thickness of 0.46m (1.5 ft) the thrust deduction $t = 0.07$ and therefore $R = T_{Bi}$. This is reasonable since the thicker ice causes loading which is equivalent (at some point) to the bollard condition where t is about 0.05. For thicker ice, negative thrust deductions are predicted. However, there is not sufficient ice thickness data on which to reliably extrapolate to large ice thickness, and therefore the existence of an operating conditions where $T_{Bi} \ll R$ should not be assumed from equations 4.2.4 and 4.2.5.

For tests in ice the scatter in t_1 is less than that of previous model data. It is expected that, on an average, thrust deduction from self-propulsion tests in ice (overload tests) would agree with the model carefully conducted clear-water overload tests. This was the result for MV ARCTIC model tests carried out in various establishments. Unfortunately no thrust data (to calculate R/T) was given with the model pull data on Figure 10 of the NSRDC report [12] and so a correlation with MOBILE BAY trials data is not possible.

Both MV ARCTIC and R Class [16] model clear-water overload tests indicate the same trend for t: No dependence on J_s and increasing with ship speed. These vessels also have quite different propulsion configurations. One would expect a good correlation between model clear-water overload data and self-propelled tests in ice provided there is no ice milling or ice ingress to the propellers.

Over the speed range in the free running condition [12], t stays reasonably constant at a value around 0.2. This is of the same order as the average values analyzed from the MOBILE BAY trials. Figures 4.2-2 and 4.2-3 do however show a strong trend toward decreasing t with increasing ice thickness. A rational explanation for this trend with ice thickness likely involves the effect of loading.

4.2.3 Wake Fraction

The wake is the difference between the forward velocity of the ship and the velocity at which the water flows to the propeller. Wake fraction in ice is defined to express the fractional change in velocity of advance of the propeller in ice-water conditions, V_{Bi}, as compared to the ship's advance velocity, V_S:

$$w_{Bi} = \frac{V_S - V_{Bi}}{V_s} = 1 - \frac{V_{Bi}}{V_s} \qquad (4.2.6)$$

where V_{Bi} is calculated by the thrust identity method. In non-ice conditions the propeller advance velocity is denoted V_A.

In the thrust identity method we assume that the K_T values derived from level icebreaking data follow the open-water propeller characteristic equation. The advance coefficient which results is interpreted as a modified advance coefficient in ice. Then multiplying by the propeller diameter D and RPM/60 will give the required advance velocity in ice:

$$V_{Bi} = n\ D\ J_{Bi} \qquad (4.2.7)$$

where J_{Bi} is the derived propeller advance coefficient. In non-ice conditions the equivalent term is J_A.

Figure 4.2.4 shows a sketch of how the thrust identity method is used to determine the propulsive factors: J_{Bi}, η_{OT} and K_{Qo}. This calculation process has been simplified by expressing the open-water propeller curves from NSRDC [12] in a numerical form:

$$K_{T_o} = 0.28405 - 0.31509(J_o) - 0.07474(J_o^2) - 0.03651(J_o^3)$$
$$K_{Q_o} = 0.3400 - 0.0365(J_o) + 0.01407(J_o^2) - 0.02412(J_o^3)$$
$$J_o = 0.7300 - 2.07181(K_{T_o}) - 1.36469(K_{T_o}^2) - 1.36944(K_{T_o}^3)$$
$$J_o = 0.80171 - 10.9172(K_{Q_o}) - 597.077(K_{Q_o}^2) + 6597.85(K_{Q_o}^3) \qquad (4.2.8)$$

Another estimation procedure based on torque identity was examined, but this resulted in wake fraction and propulsive efficiency values which were not reasonable. As discussed in Section 4.2.1, the torque coefficient K_Q in ice was a constant and not dependent on J and therefore cannot reflect changes with advance velocity.

Figure 4.2-5 shows a plot of the trials wake fractions for MOBILE BAY. A power regression which describes the relationship with J_S has the dimensionless form:

$$w_{Bi} = 0.074 J_s^{-1.394} + 0.477 \qquad (4.2.9)$$

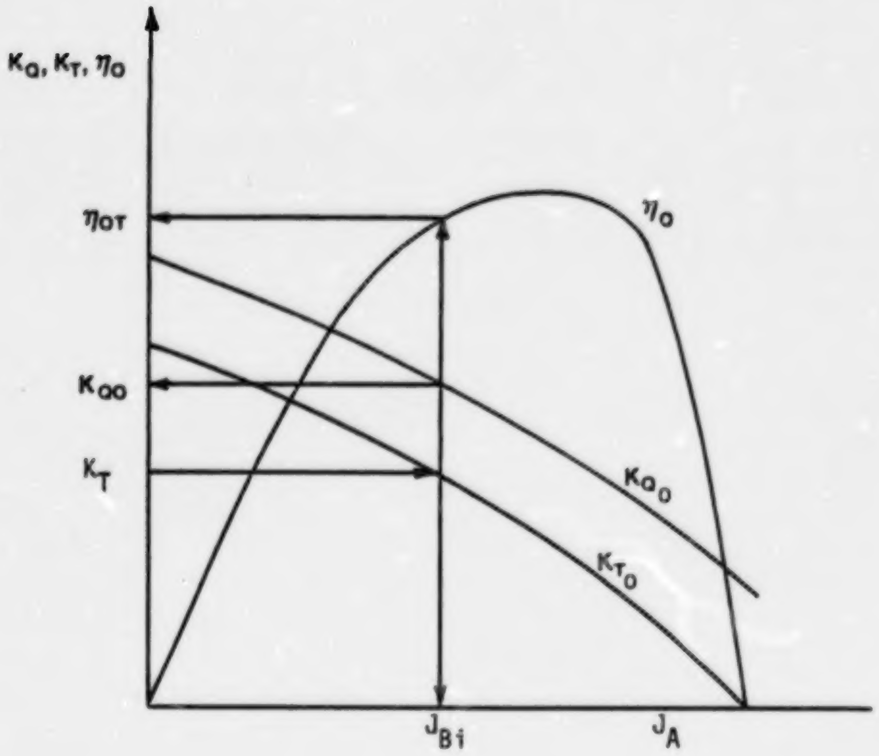

K_Q, K_T, η_O
η_{OT}
K_{QO}
K_T
η_O
K_{Q_O}
K_{T_O}
J_{Bi}
J_A

Figure 4.2-4

DEFINITION SKETCH FOR THRUST IDENTITY METHOD

This implies that w_{Bi} will approach a constant value of 0.477 at large J_s. This is a surprisingly large result in comparison to typical clear water wake values, but it is similar to results for icebreaking ships reported by Lewis [14]. In general the standard error in thrust is less than 3 percent, so it is expected that the wake fraction values are accurate. The spread between data points was much larger than the error in individual points. At small J_s values w_{Bi} increases towards positive infinity. Unfortunately there was only one data point with J_s less than 0.08 and this point has strongly influenced the numerical regression. More data at low ship velocities are required to more accurately characterize this regime for the MOBILE BAY.

The trend shown in Figure 4.2-5 is in agreement with the interpretation [14] of wake fraction illustrated in Figure 4.2-6, which was based on the KATMAI BAY overload tests. At some finite ship speed the value of V_A becomes zero. At this point the angle of attack, α, roughly equals the pitch angle, ϕ. However $J_A = 0$ is not the bollard condition since the ship is moving. V_A goes negative for smaller ship speeds. This does not mean thrust goes negative. To get data for a propeller in this regime requires overload tests where the propeller is turning ahead, but towed backwards. Unfortunately the open-water propeller results reported separately by West [12] do not include propeller overload data.

The situation depicted in Figure 4.2-6 does not necessarily apply to all icebreaker hulls. In model overload tests for an icebreaker hull and propellers, Murdey [16] has derived a trend in w towards negative infinity at the bollard condition. This has been supported by full-scale trials of the USCGC POLAR SEA [17]. Further trials and model tests of the MOBILE BAY are necessary to more accurately characterize the trend in wake fraction at small J_s values; to determine its dependence on ship parameters, and to verify this applicability of the thrust identity approach.

In addition, clear water towed trials which duplicate the procedures followed during the tests in ice covered water would be valuable. Such clear water trials would provide a reference for the 'zero thrust' RPM data obtained in the present trials, and thereby permit a better resolution of the effect of propeller-ice interactions on the measured thrust and on the calculated wake fraction.

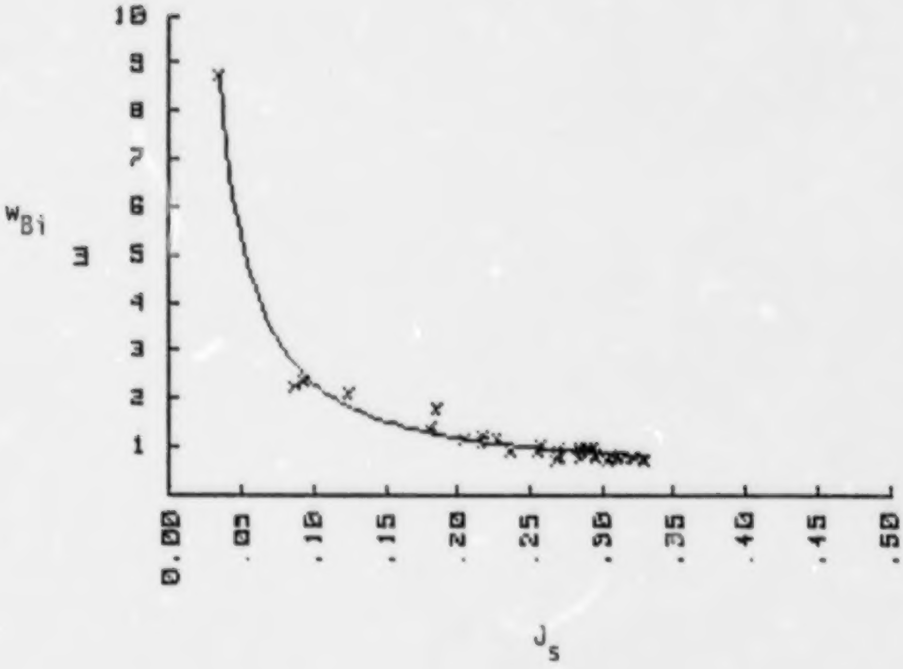
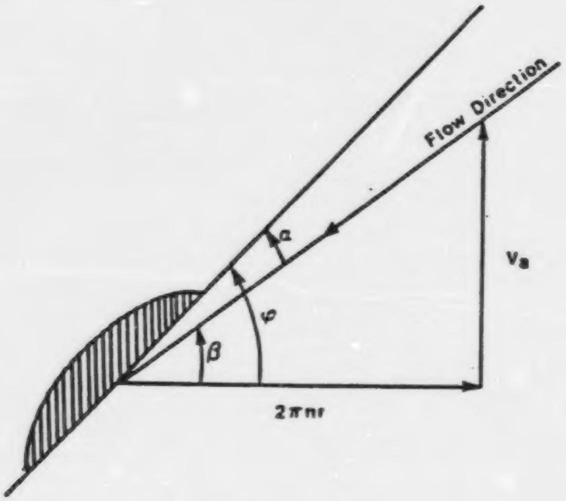
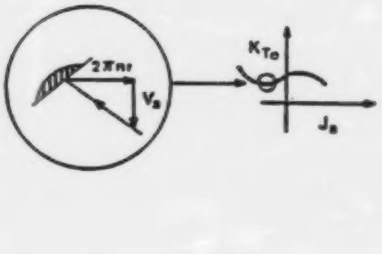


Figure 4.2-5

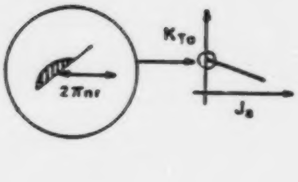
WAKE FRACTION VARIATION WITH SHIP ADVANCE COEFFICIENT


Flow Direction
α
φ
β
V_a
$2\pi nr$

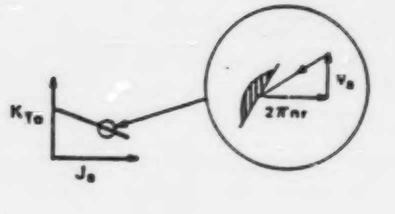
Propeller blade-velocity diagram


$2\pi nr$
V_a
K_{To}
J_a

V_A & $J_A > 0$; $0 < W < 1$
($V_S > 0$)


$2\pi nr$
K_{To}
J_a

V_A & $J_A = 0$; $W = 1$
($V_S > 0$)


K_{To}
J_a
V_a
$2\pi nr$

V_A & $J_A < 0$; $W \rightarrow 00$
($V_S > 0$)

Figure 4.2-6

DEFINITION SKETCH FOR PROPELLER ADVANCE VELOCITY IN LOADED CONDITION

4.2.4. Quasi-Propulsive Efficiency in Ice

The definition of quasi-propulsive efficiency in ice is:

$$\eta_{Bi} = \frac{\text{Useful output power}}{\text{input power}} = \frac{R_{iw} V_S}{2\pi n_{Bi} Q_{Bi}} \qquad (4.2.10)$$

where R_{iw} is total resistance in ice and water, V_S is ship velocity, n_{Bi} is RPM/60 and Q_{Bi} is measured torque.

Two η_{Bi} propulsive efficiency data sets: η_{D_1} and η_{D_2}; have been derived using resistance regression Form 1 (4.1.13) and Form 2 (4.1.16) respectively from Table 4.1-4. Trends are expected to be similar for both cases. However, the duplication again allows a check on sensitivity of efficiency to small variation in resistance.

Figure 4.2-7 and Figure 4.2-8 show η_{D_1} and η_{D_2} as functions of advance coefficient, J_s. Linear regression equations which describe each data set are:

$$\eta_{D_1} = 0.03164 + 0.8440\ J_s$$

$$\eta_{D_2} = 0.05632 + 0.7137\ J_s \qquad (4.2.11)$$

This gives a propulsive efficiency $\eta_{D_1} = 0.34$ and $\eta_{D_2} = 0.37$ for $J_s = 0.4$, arbitrary upper bound on advance coefficients in these tests. At the bollard condition the predicted efficiency is reduced to $\eta_{D_2} = 0.03$ and $\eta_{D_2} = 0.06$. The maximum efficiencies observed during the MOBILE BAY tests were: $\eta_{D_1} = 0.30$ and $\eta_{D_2} = 0.33$.

An analysis of residuals indicated that the ice thickness may be a significant variable in the efficiency equations. Therefore, a dimensionless parameter $J_s h/D$ has been formed which includes ice thickness and propeller diameter. Figure 4.2-9 and Figure 4.2-10 show a plot of this relationship and its linear regression line of this compound variable with respect to η_{D_1} and η_{D_2}:

$$\eta_{D_1} = 0.0306 + 6.087\ J_s \cdot h/D$$

$$\eta_{D_2} = 0.0724 + 4.657\ J_s \cdot h/D \qquad (4.2.12)$$

The correlation for these fits are slightly better than for J_s alone, which supports the premise that h is an important parameter. The linear character of equations 4.2.12 should not be interpreted to suggest that efficiency increases with ice thickness. The opposite trend is observed, since thicker ice will result in larger RPM and therefore smaller J_s values for a given velocity.

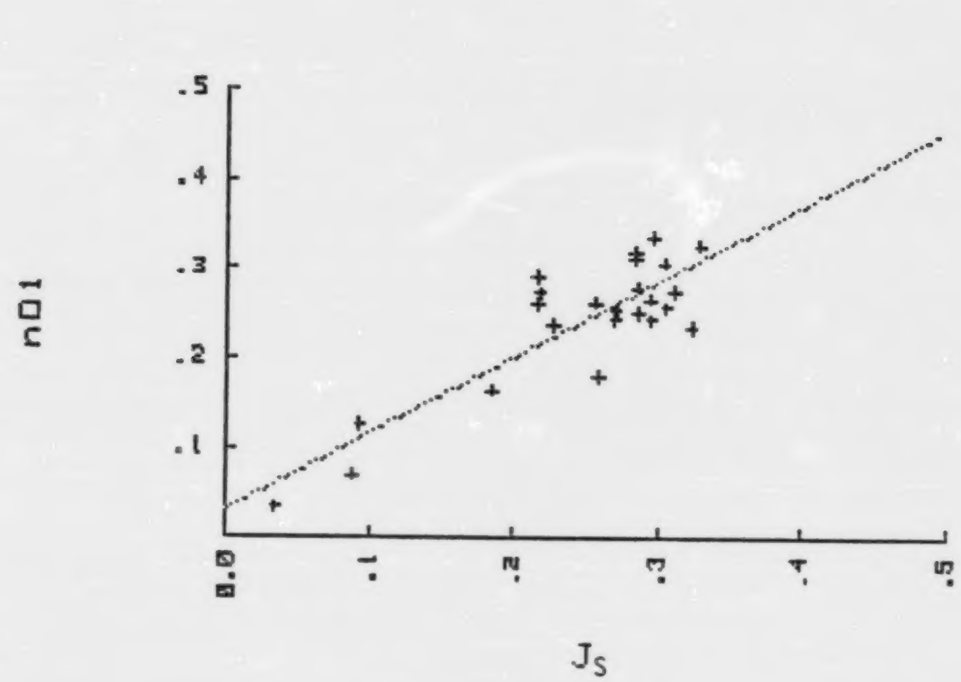


Figure 4.2-7
QUASI-PROPULSIVE EFFICIENCY (ND1) VARIATION WITH
SHIP ADVANCE COEFFICIENT

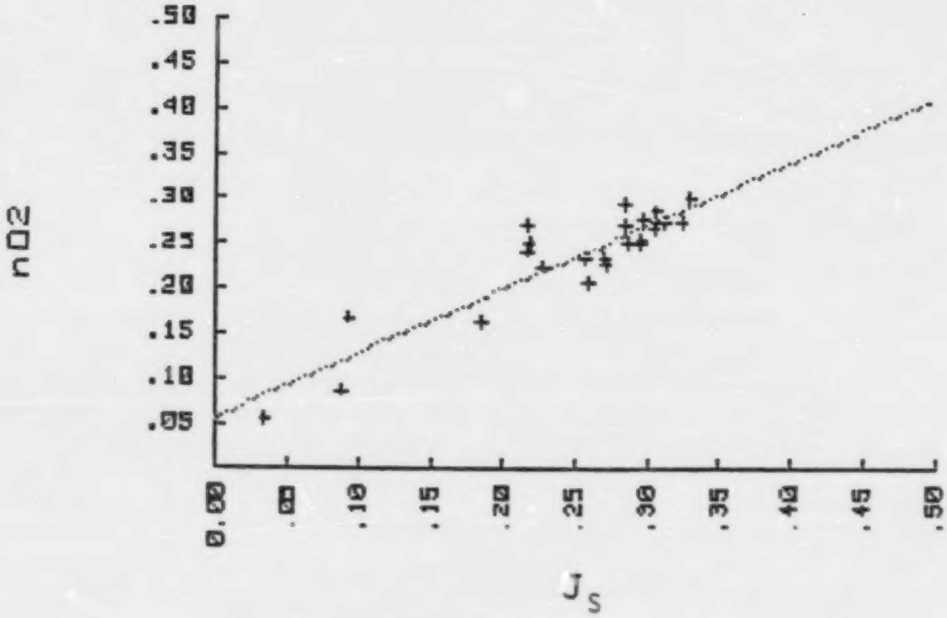


Figure 4.2-8
QUASI-PROPULSIVE EFFICIENCY (ND2) VARIATION WITH
SHIP ADVANCE COEFFICIENT

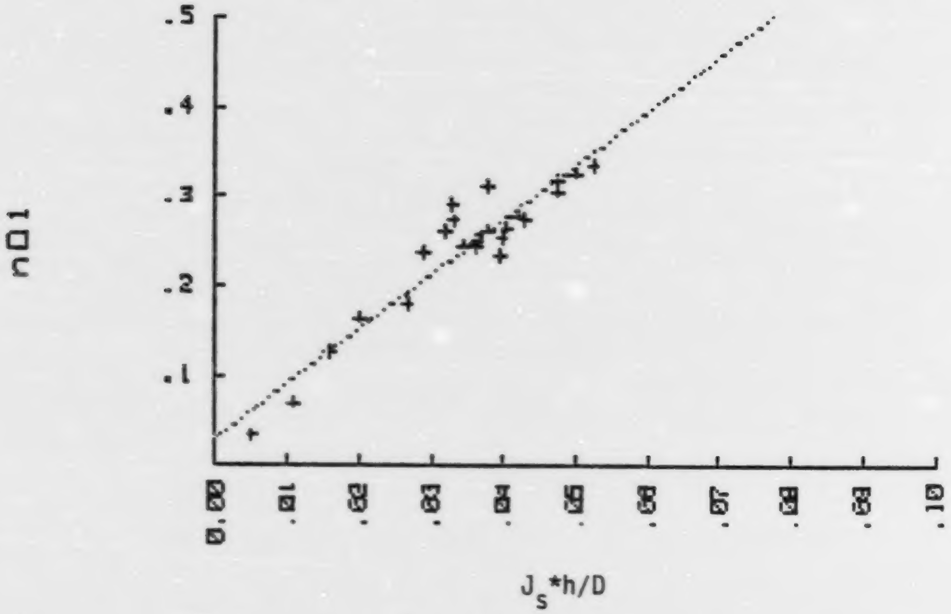


Figure 4.2-9
QUASI-PROPULSIVE EFFICIENCY (ND1) VARIATION WITH $J_s h/D$

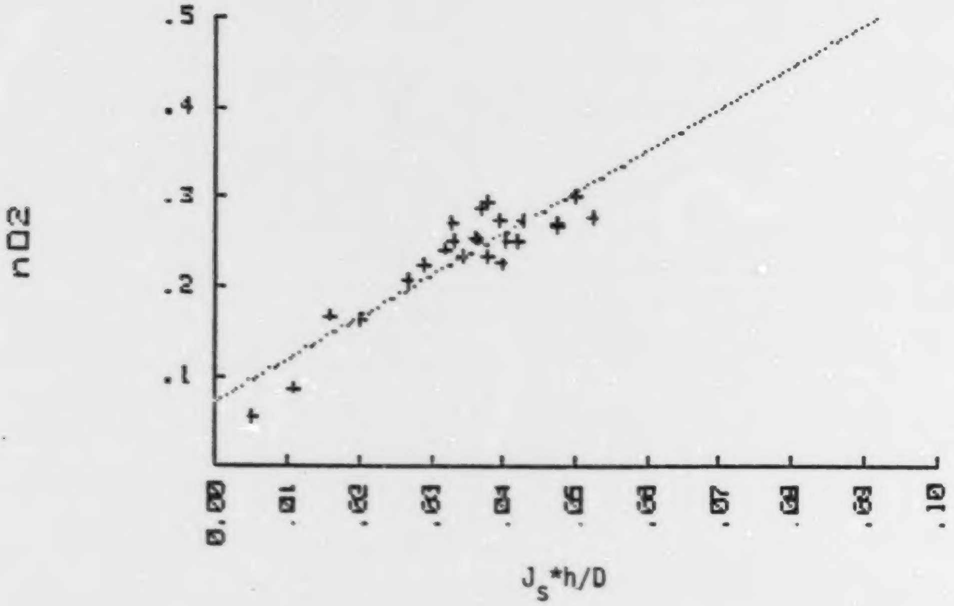


Figure 4.2-10
QUASI-PROPULSIVE EFFICIENCY (ND2) VARIATION WITH $J_s h/D$

Alternative presentations of the propulsive efficiency data are given in Figure 4.2-11 and Figure 4.2-12 which show regression lines of degree 2:

$$\eta_D 1 = -0.0236 + 10.610\ (J_s \cdot h/D) - 76.88\ (J_s \cdot h/D)^2$$

$$\eta_D 2 = -0.0041 + 11.042\ (J_s \cdot h/D) - 108.54\ (J_s \cdot h/D)^2 \quad (4.2.13)$$

A maximum is observed at $J_s \cdot h/D = 0.07$ and 0.05 for $\eta_D 1$ and $\eta_D 2$ respectively. The fit to the data is marginally better than the linear regression line; however, the small range of ice thicknesses tested does not provide a broad enough data set to verify either trend.

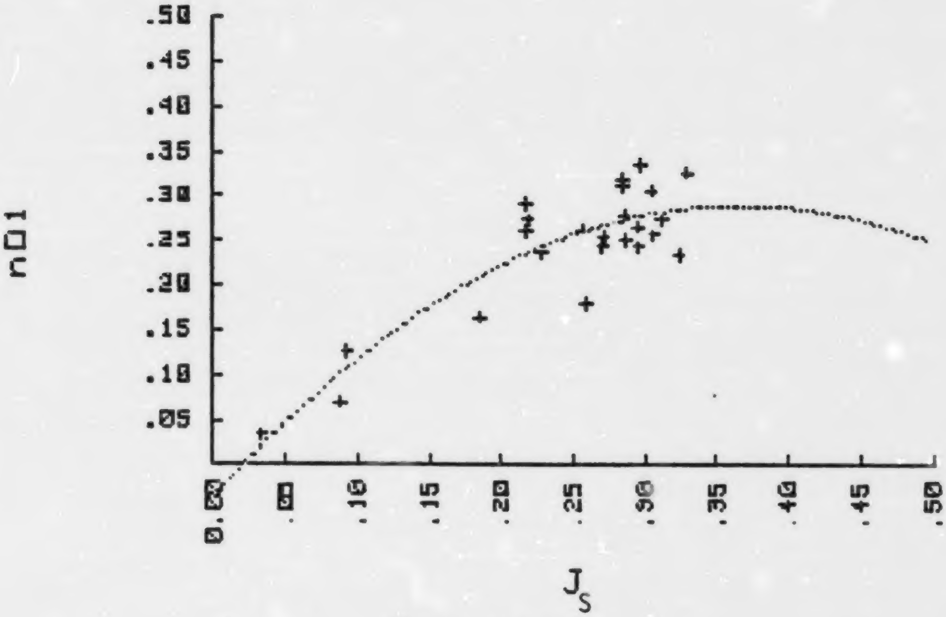


Figure 4.2-11
QUASI-PROPULSIVE EFFICIENCY (ND1) VARIATION WITH $J_s h/D$
(DEGREE 2 REGRESSION FIT)

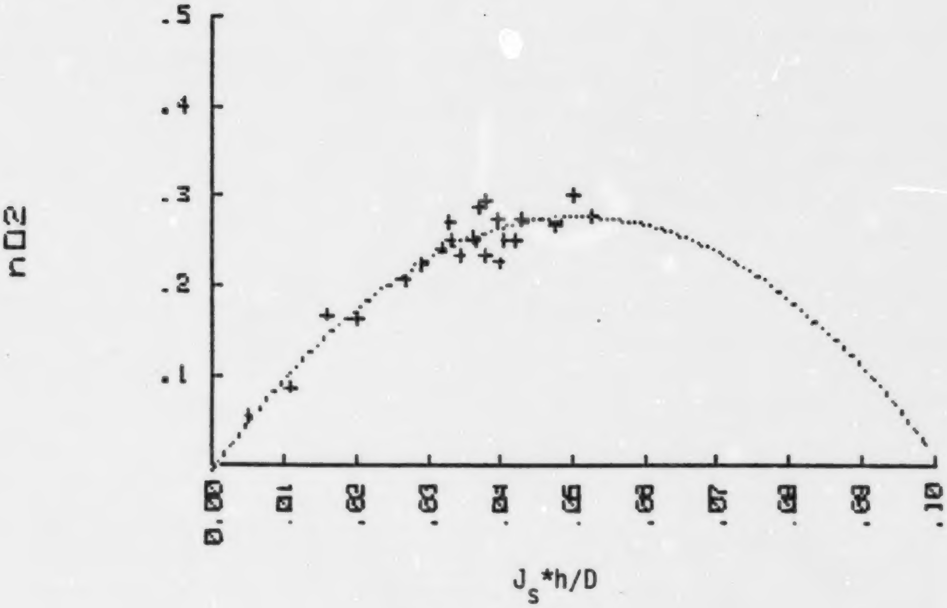


Figure 4.2-12
QUASI-PROPULSIVE EFFICIENCY (ND2) VARIATION WITH $J_s h/D$
(DEGREE 2 REGRESSION FIT)

4.2.5 Propulsive Efficiency Components

Equation 4.2.14 shows a division of the propulsive efficiency (behind a ship in ice) into seven distinct components:

$$\eta_{Bi} = \eta_h \cdot \eta_o \cdot \eta_R \cdot \eta_{HRPB} \cdot \eta_{RRPB} \cdot \eta_{HRiP} \cdot \eta_{RRiP} \qquad (4.2.14)$$

The first three components represent the traditional "ice-free, free running" breakdown of efficiencies behind a ship; with the exception of η_o This open-water efficiency term includes the influence of propeller loading associated with operating in an ice resistance environment.

In ice-free conditions the propulsive efficiency is defined as:

$$\eta_B = \frac{R_{OW}\ V_s}{2\ \pi\ n_B\ Q_B} = \frac{\text{useful output power}}{\text{input power}} \qquad (4.2.15)$$

This may be expressed in terms of the ice-free open water efficiency:

$$\eta_o = \frac{T_o V_o}{2\ \pi\ n_o\ Q_o} = \frac{KT_o J_o}{2\ \pi\ K_{Qo}} \qquad (4.2.16)$$

where the propeller boat velocity, V_o, and other independent variables are determined in open-water propeller tests. Equation 4.2.15 and 4.2.16 can be combined and reduced by means of the definition of thrust deduction and wake fraction to the form:

$$\frac{\eta_B}{\eta_o} = \left[\frac{1 - t_B}{1 - W_B}\right] \quad \frac{Q_o}{Q_B} = \eta_H \cdot \eta_R \qquad (4.2.17)$$

The first term is the hull efficiency, η_H; which represents the ratio of the power delivered to the hull to the translational output power of the propeller.

$$\eta_H = \frac{1 - t_B}{1 - W_B} = \frac{R_{OW} \cdot V_S}{T_B \cdot V_A} \qquad (4.2.18)$$

The second term of equation 4.2.17 is the relative rotative efficiency, η_R; and it represents the ratio of the propeller efficiency behind the hull to the propeller efficiency in open water. It is approximated by using the thrust identity advance velocity,

$$V_A = J_A \cdot n_B \cdot D \qquad (4.2.19)$$

which allows the following simplification:

$$\eta_R = \frac{\dfrac{T_B V_A}{2\ \pi\ n_B\ Q_{Bi}}}{\dfrac{T_O V_o}{2\ \pi\ n_o Q_o}} = \frac{Q_o}{Q_B} \qquad (4.2.20)$$

The subscript A, in J_A and V_A, has been used in this section to specifically denote the ice-free, free running condition behind a ship.

The propulsive factors: J_A, η_{OT} and K_{Qo} are defined as in Figure 4.2.4 of subsection 4.2.3 and the numerical representations of the open-water propeller curves given in equation 4.2.8 are used as algorithms in calculating the three efficiency terms.

The remaining four efficiency components in equation 4.2.14 are modifications to the hull and relative rotative efficiencies which consider the influence of the ice as a pulling effect and an ice fragment effect. Table 4.2-2 provides a summary of equations which describe the seven components.

In practice the MOBILE BAY trials did not provide data for either the ice-free, free-running condition, or for the pulling condition. The test program did not include towing in ice-free water. Furthermore, West [12] did not report his thrust data from the self-propelled tow rope pull tests, which would be required to compute η_{RHPB} and η_{RRPB}.

Therefore, in the current analysis it has only been possible to investigate trends by means of a coarser breakdown of efficiencies into cumulative hull and relative rotative components. Those have been calculated in the same manner as equations 4.2.10 and 4.2.20, with the exception that thrust deduction, wake fraction and torque are in ice:

$$\eta H_i = \frac{1 - t_{Bi}}{1 - w_{Bi}} \qquad (4.2.21)$$

$$\eta_{Ri} = Q_o / Q_{Bi} \qquad (4.2.22)$$

Figure 4.2.-13 shows the relative rotative efficiency component as a function of ship advance coefficient. It is found to decrease linearly with J_S according to the following regression equation:

$$\eta_{Ri} = 1.365 - 1.495\ J \qquad (4.2.23)$$

TABLE 4.2-2

BREAKDOWN OF PROPULSIVE EFFICIENCY COMPONENTS
SUMMARY SHEET

1. $$\eta_H = \frac{1 - t_B}{1 - w_B} = \frac{R_{OW} \cdot V_S}{T_B \cdot V_A} = \frac{R_{OW} \cdot V_S}{T_B . J_{TB} \cdot \eta_B \cdot D}$$

2. $$\eta_R = \frac{T_B}{T_0} \frac{V_A}{V_o} \frac{\eta_0}{\eta_B} \frac{Q_0}{Q_B}$$

3. $$\eta_0 = \frac{T_0 V_o}{2 \pi \eta_0 Q_0} = \frac{K_T J}{2 \pi K_Q}$$

4. $$\eta_{HRPB} = \frac{P+R_{OW}}{R_{OW}} \cdot \frac{T_B}{T_{BP}} \cdot \frac{J_B}{J_{BP}} \cdot \frac{\eta_B}{\eta_{BP}}$$

(T or Q Ident. for J_B & J_{BP})

5. $$\eta_{RRPB} = \frac{T_{BP}}{T_B} \cdot \frac{J_{BP}}{J_B} \cdot \frac{Q_B}{Q_{BP}}$$

6. $$\eta_{HRIP} = \frac{R_{iw}}{P+R_{OW}} \cdot \frac{T_{BP}}{T_{Bi}} \cdot \frac{J_{BP}}{J_{Bi}} \cdot \frac{\eta_{BP}}{\eta_{Bi}}$$

(Thrust or Torque Identity)

7. $$\eta_{RRIP} = \frac{T_{Bi}}{T_{BP}} \cdot \frac{J_{Bi}}{J_{BP}} \cdot \frac{Q_{BP}}{Q_{Bi}}$$

$$\Big\} \frac{\eta_B}{\eta_0} = \frac{R_{OW}}{T_0} \frac{V_A}{V_o} \frac{1}{1-w_B} \frac{\eta_0}{\eta_B} \frac{Q_0}{Q_B}$$

$$\Big\} \eta_B = \frac{R_{OW} \left(\frac{V_A}{1-w_B}\right)}{2 \pi \eta_B Q_B}$$

$$\Big\} \frac{\eta_{BP}}{\eta_B} = \eta_{HRPB} \cdot \eta_{RRPB} = \frac{P+R_{OW}}{R_{OW}} \cdot \frac{\eta_B}{\eta_{BP}} \cdot \frac{Q_B}{Q_{BP}}$$

Avoids T or Q Identity Method for BP

$$\Big\} \frac{\eta_{Bi}}{\eta_{BP}} = \eta_{RRIP} \cdot \eta_{RRIP} = \frac{R_{iw}}{P+R_{OW}} \cdot \frac{\eta_{BP}}{\eta_{Bi}} \cdot \frac{Q_{BP}}{Q_{Bi}}$$

Avoids T or Q Identity Method for Bi

Subscripts:

A	Advance
B	Behind ship in clear water
BP	Behind pulling condition in clear water
Bi	Behind pulling in ice
iw	Ice and water total
O	Open water propeller test results
OW	Clear water results
H	Hull
R	Relative rotative
HRPB	Hull, behind pulling
HRIP	Hull, in ice pulling
RRPB	Relative rotative, behind pulling
RRIP	Relative rotative, in ice pulling

From an examination of residuals it was found that a trend appeared to exist between η_{Ri} and ice thickness, h, and therefore a dimensionless parameter $J_s \cdot h/D$ was formed. Figure 4.2-14 shows this presentation of the data. A better correlation is obtained for the resulting regression equation:

$$\eta_{Ri} = 1.339 - 9.263\ J_s \cdot h/D \qquad (4.2.24)$$

A greater range of ice thickness data would be required to further define the influence of h and J_s. A maximum η_{Ri} of approximate 1.35 is extrapolated for the bollard condition. This reduces to 0.77 at an arbitrary upper bound value of $J_s = 0.4$.

In Figure 4.2-15 η_{Ri} is shown to follow an increasing trend with K_T. This is consistent with the variation with Js, since both argue that η_{Ri} increases towards the heavily loaded bollard condition, at which $J_s = 0$.

The hull efficiency in ice, η_{Hi}, is shown in Figures 4.2-16 and 4.2-17. No significant trend with ice thickness is observed. Nor was any variation of hull efficiency from a constant value observed, although there is a large scatter in the data points.

It was noted in Section 4.2.4 that thrust deduction did not show a significant variation with J_s. Wake fraction decreased with J_s and therefore the overall expression (equation 4.2.21) was expected to increase. Thrust deduction also depended on ice thickness; while no significant influence on wake fraction was observed. However, the net outcome of equation of 4.2.21 showed no trend with either variable.

The total quasi-propulsive coefficient in Section 4.2.4 is calculated independently of the three component efficiencies η_o, η_{Ri}, η_{Hi}. Nonetheless the cumulative product of the components agrees numerically and in its trends with the directly calculated η_{D1} and η_{D2}.

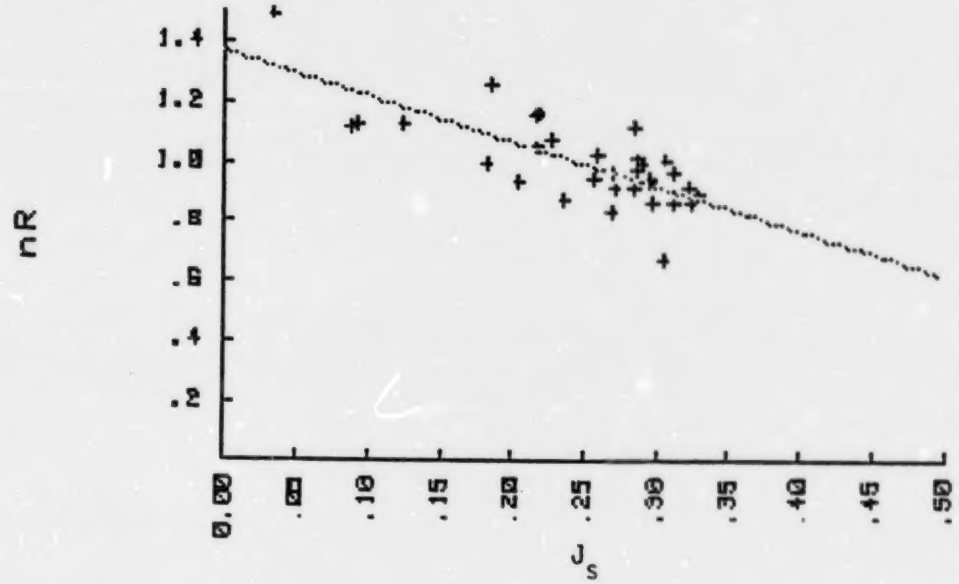


Figure 4.2-13
RELATIVE ROTATIVE EFFICIENCY VARIATION WITH ADVANCE COEFFICIENT

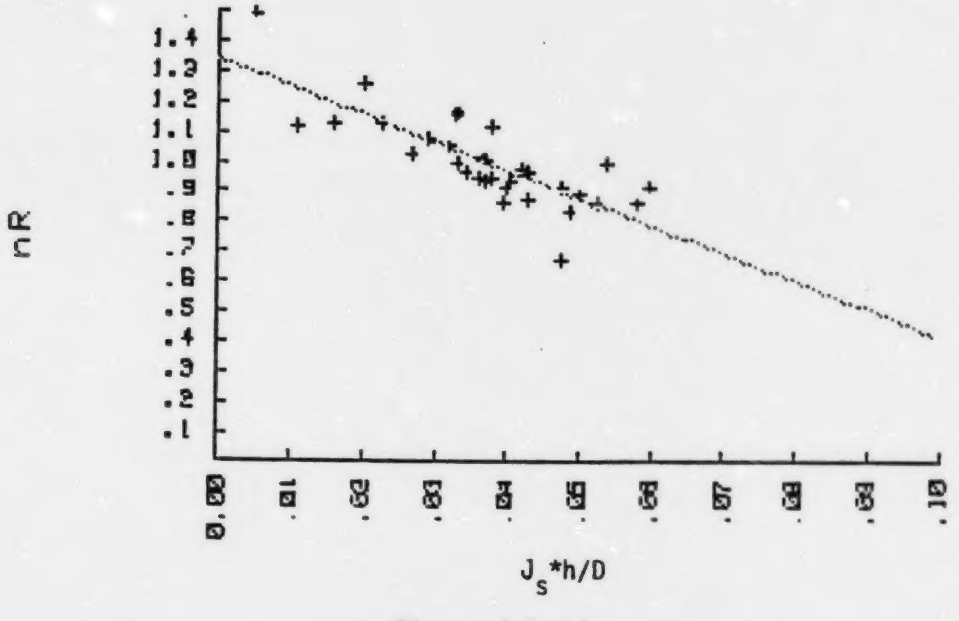


Figure 4.2-14
RELATIVE ROTATIVE EFFICIENCY VARIATION WITH $J_s h/D$

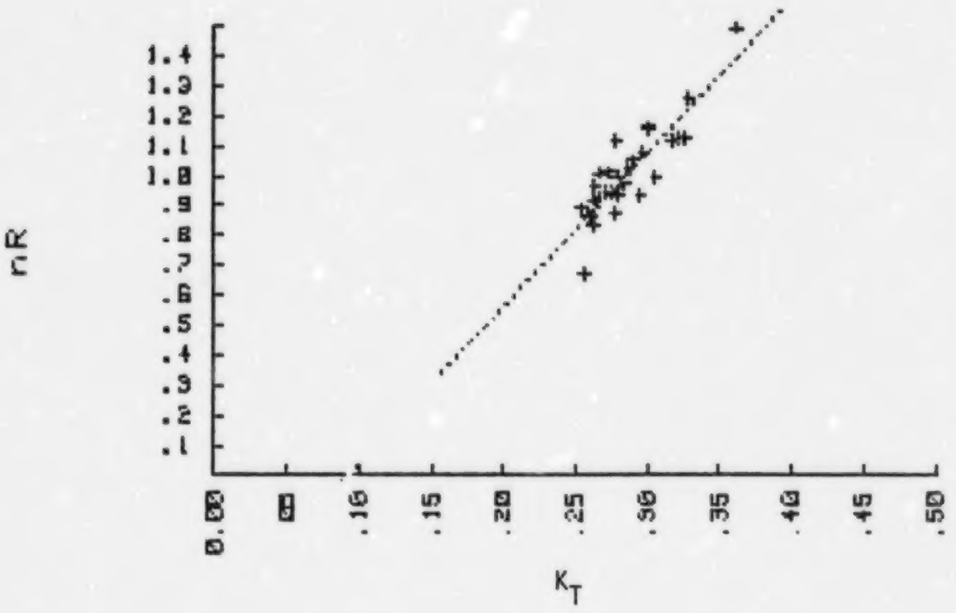


Figure 4.2-15
RELATIVE ROTATIVE EFFICIENCY VARIATION WITH K_T

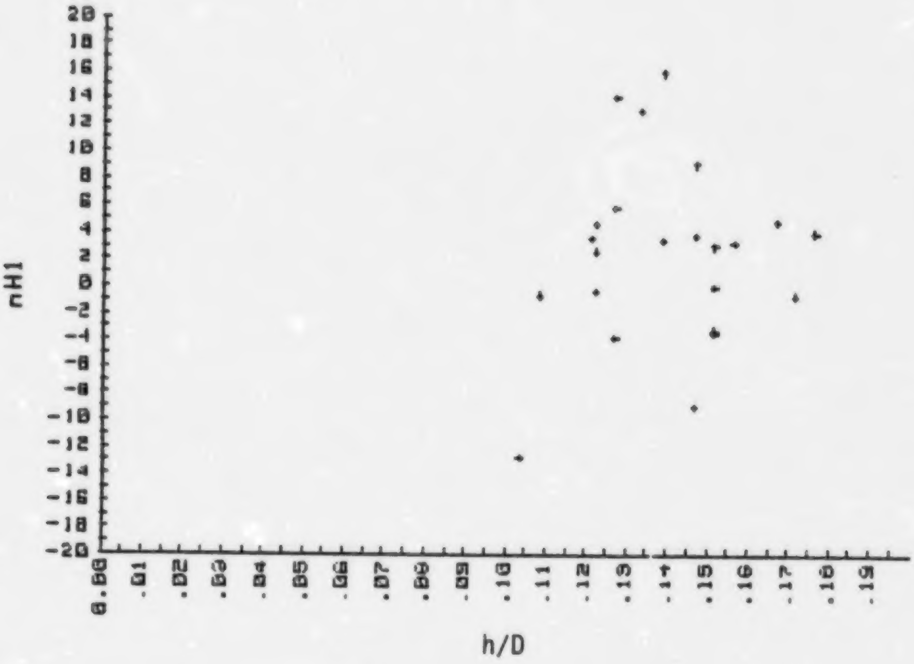


Figure 4.2-16
HULL EFFICIENCY (NH1) VARIATION WITH ICE THICKNESS

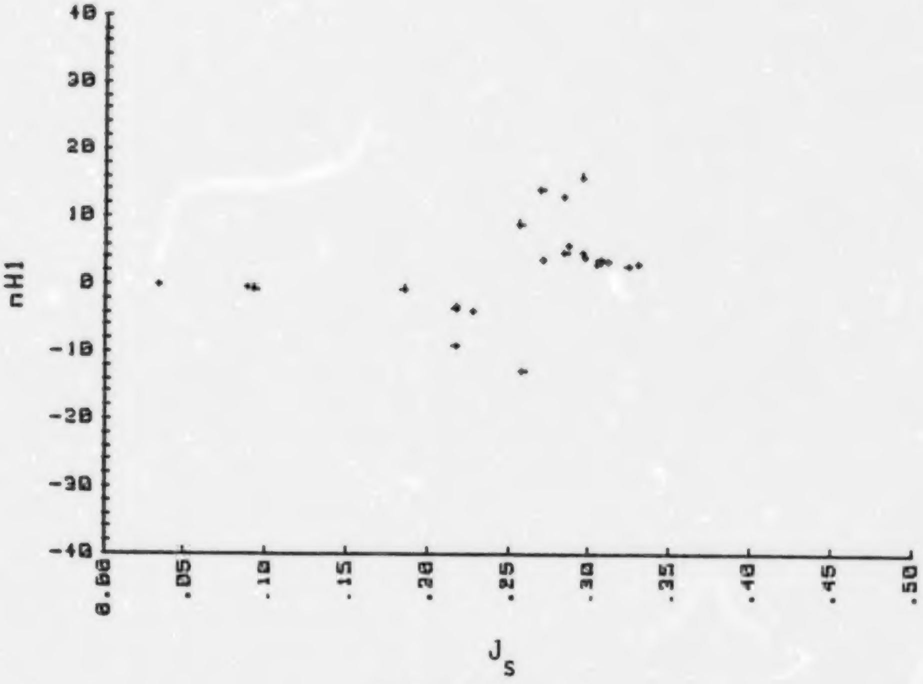


Figure 4.2-17
HULL EFFICIENCY (NH1) VARIATION WITH ADVANCE COEFFICIENT

4.2.6 Comparison to KATMAI BAY Trials and Model Test Data

The data obtained in the KATMAI BAY self-propulsion trials has been re-analyzed and compared to the MOBILE BAY results. Table 4.2-3 gives the basic data from those trials. Table 4.2-4 shows the propulsive coefficients which are derived using the KATMAI BAY measured self-propulsion data and the towed resistance from the MOBILE BAY trials. The two resistance formulations discussed in Section 4.2.4 for the MOBILE BAY propulsive coefficients have again been used here.

Table 4.2-5 reproduces CRREL model test data for MOBILE BAY (140' WTGB hull form) and shows propulsive coefficients which resulted. It should be noted that only six data points are available at model scale and therefore all conclusions are tempered by this lack of coverage of ice thicknesses and speeds.

Figure 4.2-18 shows thrust deduction results based on resistance form 1 for KATMAI BAY. A decreasing trend with J_S is observed which is very similar to that for MOBILE BAY. The results are again strongly dependent on ice thickness. The CRREL model tests predict a thrust deduction value of about 0.26 for $J_S = 0.13$ and 4.6cm ice, higher than an estimate of 0.1 from equations 4.2.4 or 4.2.5 for MOBILE BAY results. However scatter in the MOBILE BAY and KATMAI BAY thrust deduction results makes it difficult to assess the importance of this variation from the regression line.

Wake fraction results from the KATMAI BAY trials are plotted along with the MOBILE BAY regression curve in Figure 4.2-19. An excellent correlation is observed. The agreement is much poorer for the CRREL model scale wake values; with the model test values grossly underpredicting the equivalent full-scale values. This is a significant finding, even though only a few data points are available from one model basin and spanning a narrow range of J_S. Additional model scale propulsion tests in different ice materials would be of great value in assessing the extent of this problem.

Relative rotative efficiency is shown in Figure 4.2-20. A decreasing tendency of η_{Ri} with J_S is observed in the KATMAI BAY results, which agrees well with MOBILE BAY trends. The CRREL model scale predictions appear marginally low. At $J_S = 0.13$ and $h = 0.46$m (1.5 ft) the model scale value of η_{Ri} is 0.97. The MOBILE BAY trials prediction is 1.13 from equation 4.2.24.

The quasi-propulsive coefficient $\eta_D{}^1$ for is plotted in Figure 4.2-21. Excellent agreement is seen between the MOBILE BAY and KATMAI BAY predictions. The CRREL model scale predictions appear to agree well with both trials data sets. However, if the ice thickness is assessed by comparing the model predictions with equation 4.2.12 or 4.2.13 it is seen that their mean value of 0.125 is 30% lower than the expected value of 0.18.

In view of the higher ice strengths and uncertainty in friction coefficients in these model tests, a reduced efficiency is plausible. Future model test programs should therefore extend the speed and thickness ranges and investigate the influence of variation in ice strength and ship/ice friction.

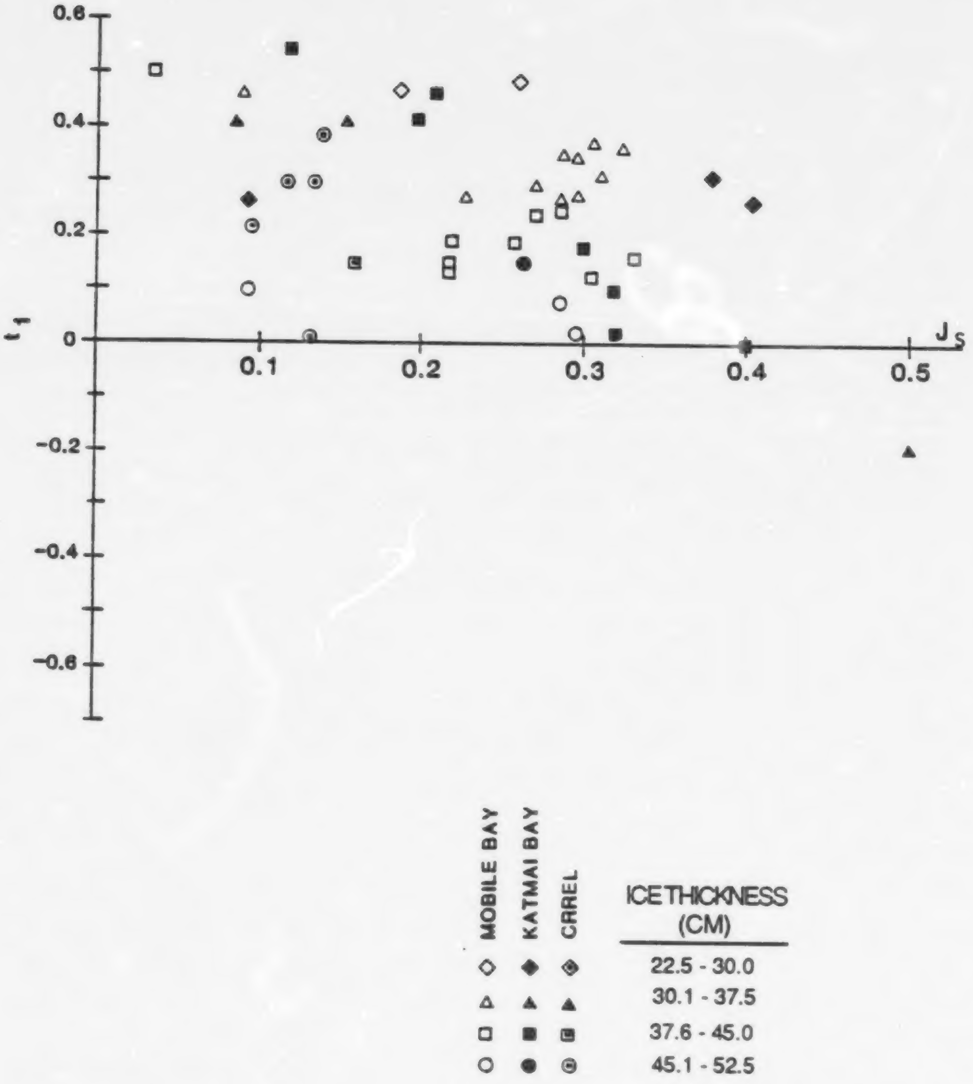


Figure 4.2-18

THRUST DEDUCTION (t1) COMPARISON TO KATMAI BAY AND CRREL RESULTS

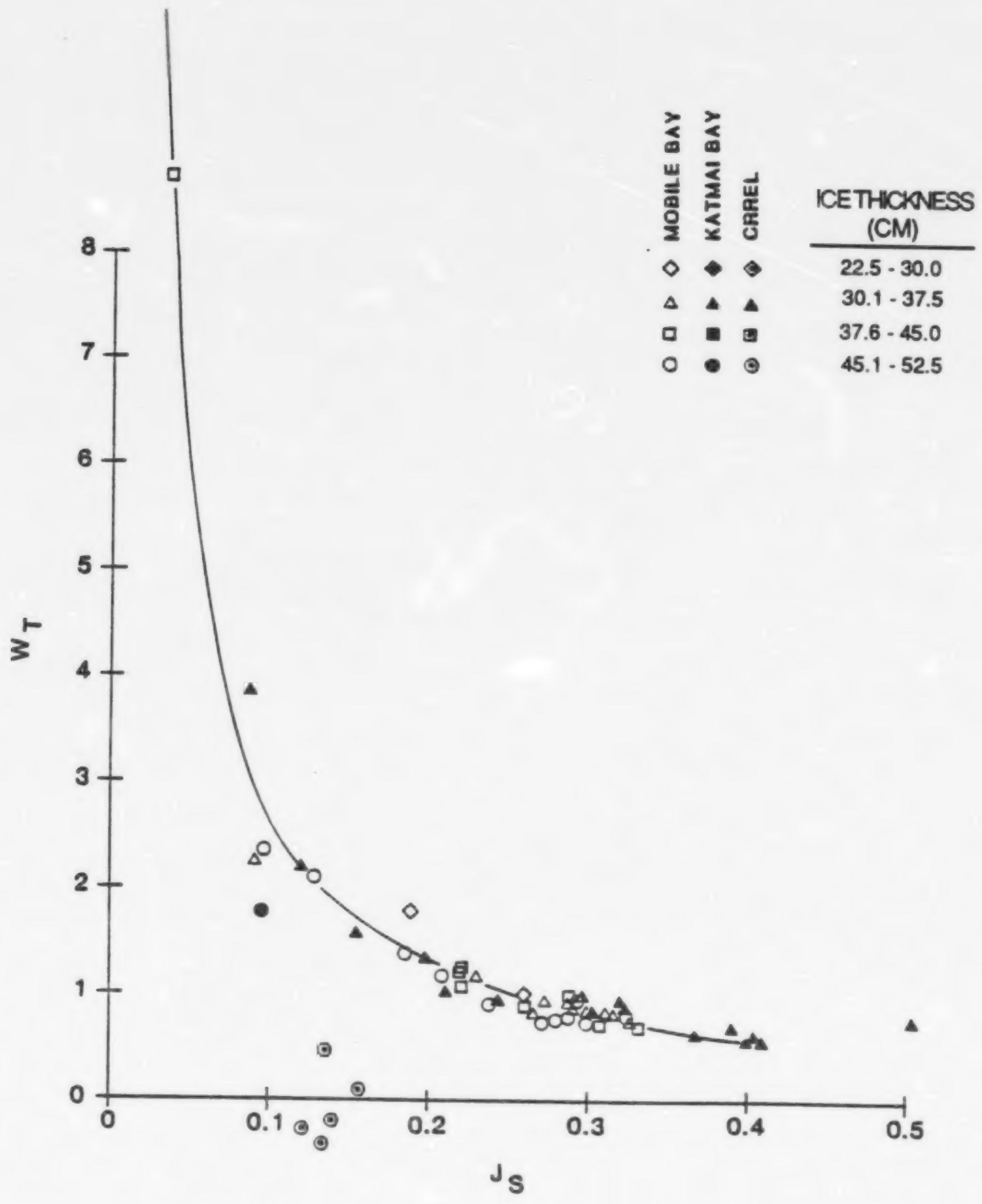


Figure 4.2-19

WAKE FRACTION COMPARISON TO KATMAI BAY AND CRREL RESULTS

TABLE 4.2-3

KATMAI BAY TRIALS DATA (1980)

TEST	V (kts)	h (m)	n (RPM)	J_s	T (N)	Q (N.m)
1000	3.2	0.305	148.1	.153	85526	24126
1010	9.4	0.381	208.9	.318	149166	48512
1020	13.1	0.280	244.9	.378	185031	65298
1030	14.8	0.280	258.7	.404	196300	74953
1100	1.6	0.357	132.7	.085	78595	19843
1110	9.1	0.369	213.9	.300	154023	49597
1120	17.8	0.357	252.4	.498	191100	67151
1130	15.1	0.381	266.9	.399	203216	71928
1200	9.2	0.381	203.7	.319	144570	47500
1210	12.2	0.329	236.7	.364	169419	60643
1220	14.8	0.280	263.1	.397	196148	71983
1300	3.2	0.381	192.3	.117	191257	41944
1310	6.1	0.405	219.4	.196	183488	53597
1320	8.4	0.419	246.9	.240	213087	67854
1330	7.3	0.405	250.4	.206	224723	74852
1340	9.4	0.497	254.3	.261	217931	73967

TABLE 4.2-4A

REANALYSIS OF KATMAI BAY TRIALS DATA

	‡h /D	J_s	K_T	$10\ K_Q$	t_1	t_2
1000	0.118	0.1525	0.3116	0.3393	0.4067	0.38897
1010	0.147	0.3176	0.2732	0.3429	0.0972	0.1847
1020	0.108	0.3776	0.2466	0.3358	0.3111	-0.0697
1030	0.108	0.4038	0.2344	0.3455	0.2615	-0.2578
1100	0.138	0.0851	0.3567	0.3476	0.4091	0.2300
1110	0.142	0.3003	0.2690	0.3344	0.1812	0.2476
1120	0.138	0.4978	0.2397	0.3252	-0.1954	-0.5581
1130	0.147	0.3994	0.2280	0.3115	-0.0035	-0.0763
1200	0.147	0.3188	0.2784	0.3531	0.0838	0.1753
1210	0.127	0.3638	0.2417	0.3339	0.1608	0.0347
1220	0.108	0.3971	0.2265	0.3208	0.2609	-0.2588
1300	0.147	0.1175	0.3269	0.3499	0.5433	0.5114
1310	0.156	0.1963	0.3046	0.3435	0.4113	0.4703
1320	0.162	0.2402	0.2794	0.3434	0.3470	0.4399
1330	0.156	0.2058	0.2864	0.3683	0.4597	0.5276
1340	0.192	0.2609	0.2693	0.3528	0.1474	0.3026

‡ NOTE: D = 2.6m (8.5 ft)

TABLE 4.2-4B

REANALYSIS OF KATMAI BAY DATA

(Continued)

TEST	W	η_{D1}	η_{D2}	η_R
1000	1.587	0.1323	0.1362	1.103
1010	0.8920	0.3636	0.3283	0.9551
1020	0.6936	0.3039	0.4719	0.8899
1030	0.6243	0.3221	0.5485	0.8293
1100	3.876	0.0821	0.1070	1.272
1110	0.8429	0.3149	0.2893	0.9657
1120	0.7267	0.6983	0.9102	0.8976
1130	0.5731	0.4669	0.5007	0.8992
1200	0.9443	0.3666	0.3300	0.9445
1210	0.6419	0.3517	0.4045	0.8801
1220	0.5594	0.3297	0.5616	0.8684
1300	2.200	0.0798	0.0853	1.130
1310	1.339	0.1631	0.1467	1.063
1320	0.9380	0.2031	0.1742	0.9744
1330	1.037	0.1376	0.1203	0.9309
1340	0.8226	0.2703	0.2211	0.9161

TABLE 4.2-5

CRREL SELF-PROPULSION DATA (By Interpolation)

A. BASIC DATA

TEST SERIES	h (cm)	V (cm/s)	T (N)	Q (Nm)	R_T (N)	n (RPM)
100	5.2	33.5	317	10.8	246.3	782
200	4.9	52.0	317	11.0	222.5	846
300	5.3	66.7	426	12.2	261	1046
400	5.3	51.0	346	12.1	243	932
500	4.8	50.3	249	11.5	247.2	814
600	4.2	50.4	194	7.9	166.3	695

B. DIMENSIONLESS PROPULSIVE COEFFICIENTS

TEST SERIES	J_s	KT	10x KQ	t	w	η_D	η_R
100	.092	0.306	0.373	0.223	1.774	0.093	1.019
200	0.132	0.262	0.325	0.298	0.474	0.119	0.895
300	0.137	0.230	0.236	0.387	-0.204	0.130	1.229
400	0.117	0.236	0.294	0.298	-0.254	0.105	1.014
500	0.132	0.222	0.367	0.008	-0.418	0.127	0.793
600	0.155	0.238	0.346	0.144	0.092	0.146	0.821

D = 0.279m (11 in.)
SCALE = 1:9.273

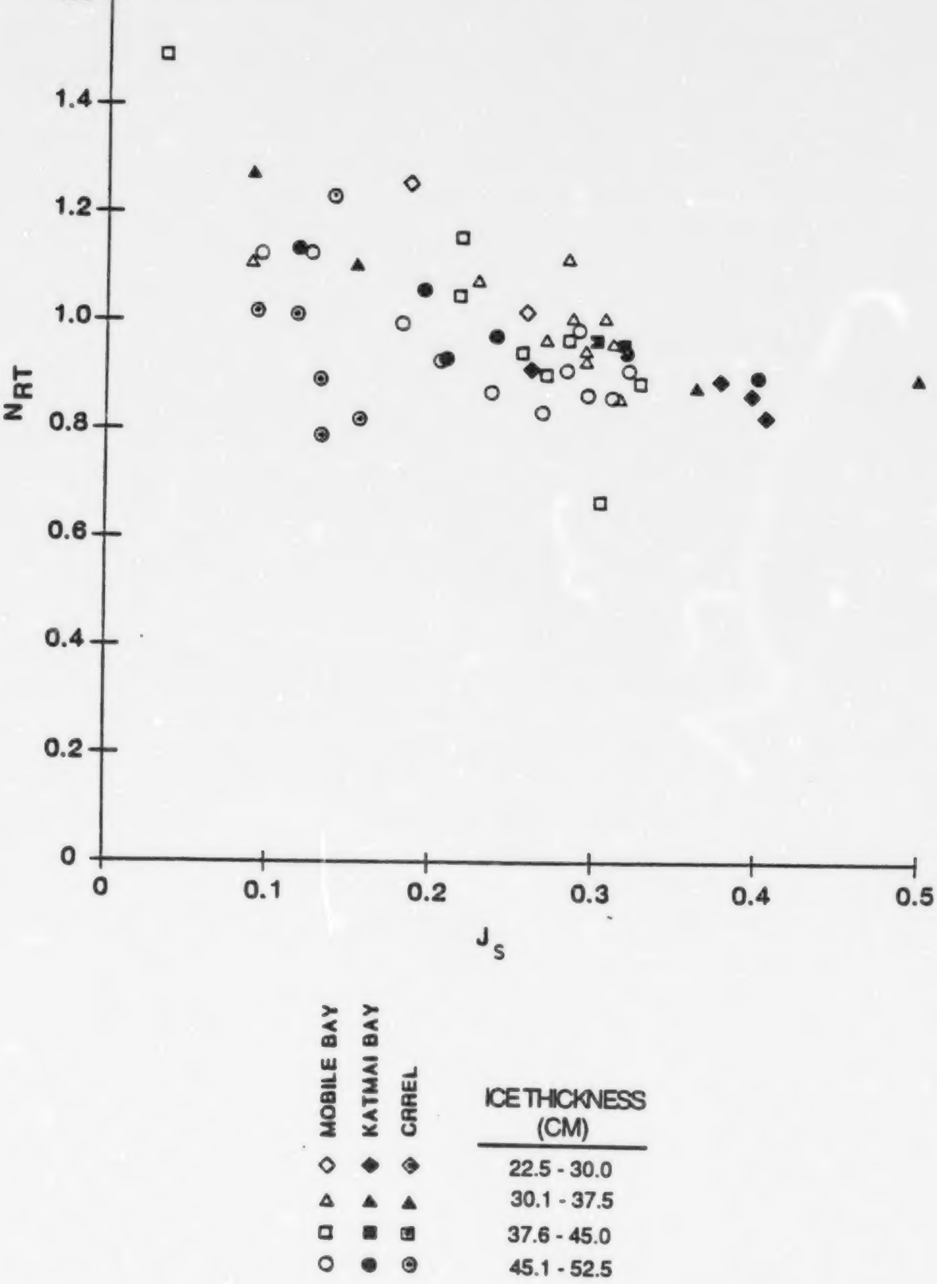


Figure 4.2-20

RELATIVE ROTATIVE EFFICIENCY COMPARISON TO KATMAI BAY AND CRREL RESULTS

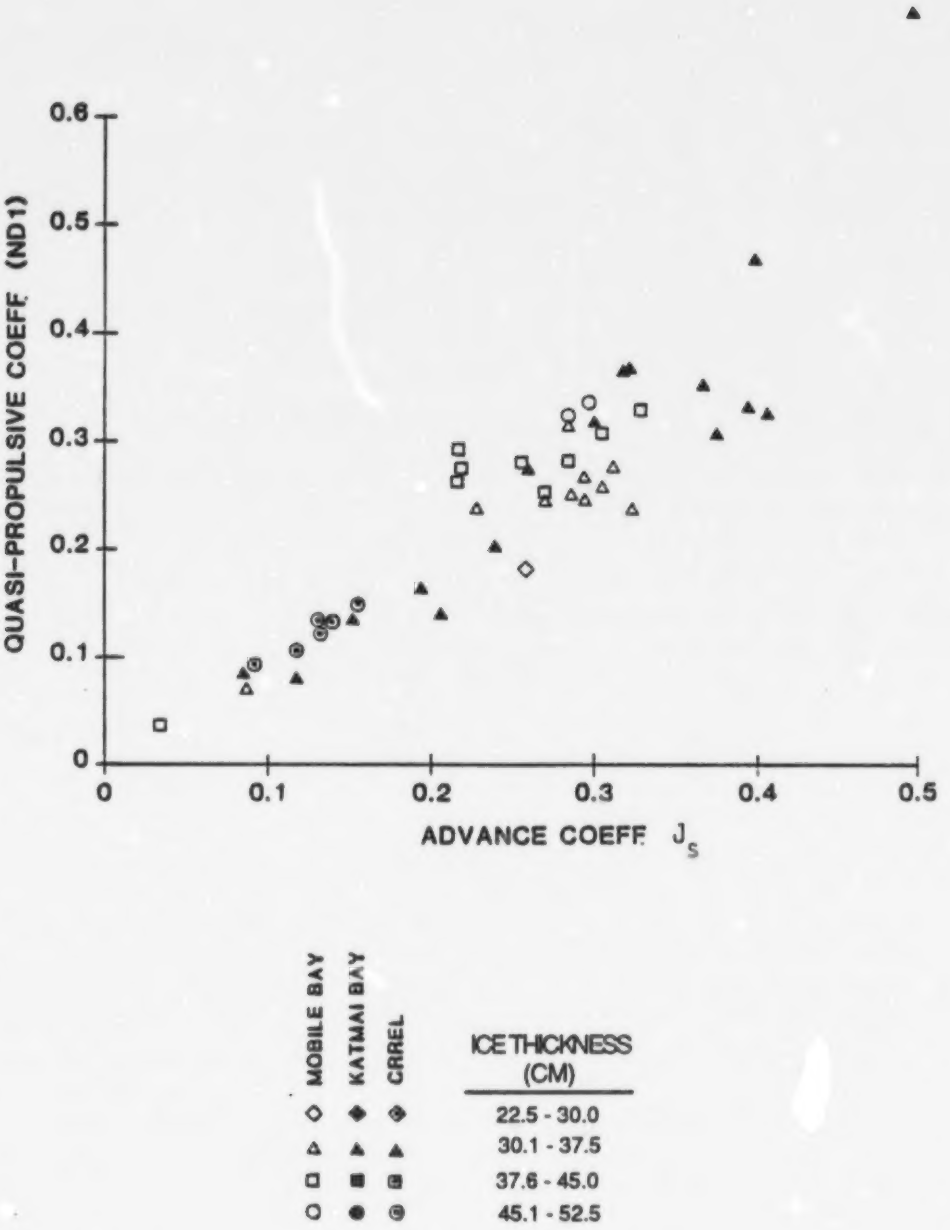


Figure 4.2–21

QUASI–PROPULSIVE EFFICIENCY COMPARISON TO KATMAI BAY AND CRREL RESULTS

Tatinclaux [19] has recently reported another set of model scale propulsion data which considers the propulsive performance of the KATMAI BAY in pre-cut ice. The 1:10 (9.273) scale WTGB hull form was again used. Testing was carried out in 5 cm urea ice for a range of floe sizes and in brash ice. An attempt was made to establish an upper bound to the trends associated with floe size and therefore a majority of the tests involved very large (40 cm x 60 cm) floes. As a result of a malfunction in the thrust dynamometer, only torque data was obtained. However, many of the conclusions have a striking similarity to the towed trials propulsion results. In particular:

- K_Q in ice-free operations was found to decrease with increasing J_s; whereas in the very large urea ice floes K_Q increased rapidly with J_s. In brash ice, it remained constant or increased very slowly. K_Q also increased linearly with floe width over the range tested.

- The standard deviation in the torque, σ_Q, was independent of velocity in the ice-free model condition. In large urea ice floes it was observed that there was an increased level of fluctuation in torque with V indicating an increase in ice ingestion and propeller-ice interactions. Hence σ_Q was approximately constant in brash ice at lower velocities, but increased at higher velocities. Increasing floe size at constant velocity resulted in an increase in σ_Q.

- The dominant frequency, f, in the torque time histories at model scale was observed to be:

  $$f = V/W$$

  or multiples of that ratio; where W is the floe width

The trials results have shown a similar increase in K_Q as found in the model tests; although only slightly in excess of a constant value equivalent to the bollard condition. However a comparison of torque signals clearly shows that there is a greater severity of propeller ice interaction in the model tests. This may be due to the excessive crushing strength of model ice at its nominally correct flexural strength. In this respect, the towed trials K_Q trend in unbroken ice appears closer to the model scale brash ice test results. The scatter in full scale torque was observed to only increase slightly with velocity, as shown in Figure 4.2.1, although the frequency of ice encounters in the towed trials increases significantly above 4 knots.

Although there may be many ice modelling parameters which affect the details of the model scale propulsion results, it appears that in general they support the trends observed in the towed trials. If the model ice breaks into floes which are much larger than prototype ice cusps then the torque and corresponding power prediction will be exaggerated. The influence of increased ship velocity in causing increased ice ingestion and propeller-ice milling is observed at both scales. The specific gravity of the urea-doped model ice is identified as an important parameter which determines the amount of ice which reaches the propellers. In a separate assessment of the literature, Abdelnour [20] also concluded that density differences may affect the amount of entrainment. Since urea ice has a specific gravity of 0.94, which is greater than for fresh water ice or sea ice, the buoyancy forces will be less and therefore ice pieces will rise more slowly. This means that ice pieces which in full scale would rise along the ship's sideshell, remain under the model hull and reach the propellers. Consequently the model scale hull-ice friction coefficient is incorrect, the amount of secondary crushing along the side shell is reduced and the trajectories of ice into the propellers are elongated. This is viewed as the principal source of distortion in the ice modelling process. These concerns are reflected in the correlation of model to full scale results by the importance assigned to the proper modelling of hull-ice friction. However it appears that density, piece-size distribution and other factors influence the effective friction and must also be further examined.

4.2.7 Summary of Analysis Results

In summary, the regression analyses on the MOBILE BAY trials data have identified a series of trends which have important implications for the prediction of propulsive performance by model tests and full-scale trials. The significant results from the MOBILE BAY trials are as follows:

- The two principal resistance estimation forms selected from Section 4.1 consistently reproduced equivalent regression equations for thrust deduction, wake fraction and other propulsive coefficients.

- The KATMAI BAY self-propulsion data is in excellent agreement with the MOBILE BAY results. The data sets are virtually interchangeable and produce equivalent trends in the propulsive coefficients when the MOBILE BAY resistance equations are used.

- Thrust deduction fraction was found to be strongly correlated to ice thickness, with a linear decrease from 0.5 to zero over the range of thicknesses tested. There was no significant correlation with ship advance coefficient. The thrust deduction which is predicted as ice thickness approaches zero is about 1.0, i.e. net $T = 0$ which is much grater than the expected ice-free, free-running value of 0.3. This has suggested that an additional term may be required in the regression equation which reflects the influence of ice thickness on the load experienced by the propeller. This term would likely include ship displacement and propeller diameter. however no trials data is available to verify whether or not the linear trend is indeed modified in the thin ice regime, such that a maximum thrust deduction occurs with consequent lower values at zero ice thickness. For thick ice the thrust deduction is reasonable since it corresponds to open-water bollard values. A plausible explanation for the smaller thrust deduction in thicker ice is that the hydrodynamic effects at any speed are relatively constant and therefore have a diminished importance as the ice loading increases.

- No thrust deduction variation with ship advance coefficient has been identified, and therefore it does not appear to be velocity dependent. However, the tested range of advance coefficient was limited and may not have been broad enough to verify this result. Further trials with a large variation in advance coefficient are required to allow a clearer definition of these trends.

- Wake fraction has been found to strongly depend on ship advance coefficient. It decreases from positive infinity at the bollard condition and approaches a constant value near 0.5 at large values of advance coefficient. This trend is similar to that reported from the 140′ WTGB model tests at CRREL, but numerically different. The model tests grossly underpredicted the trials values. Other investigations at model scale and full-scale for multiple screw icebreaking ships have resulted in very different trends in the low advance coefficient regime, but similar magnitudes of wake fraction over the principal higher range of advance coefficients observed in the MOBILE BAY tests. The variation in trend should be further studied either with additional trials or with a parametric model test program; provided that the model ice gives a better numerical correspondence to the MOBILE BAY results, than was attained at CRREL with urea ice. It was noted in Section 4.1.2 that saline ice at ARCTEC gave a much better resistance estimate than urea ice. However its applicability to wake fraction estimates could not be assessed since no 140' WTGB self-propulsion tests were carried out in the saline ice.

- There were two major characteristics of the ice-water propeller curves. Torque coefficient, K_Q, was found to remain constant with increasing J_s. In open water K_Q generally follows a downward sloping line with respect to advance coefficient. If the influence of increased ice thickness is taken into account, the constant K_Q value approximates to be necessary to ascertain whether K_Q would exceed the open-water bollard value. The thrust coefficient in ice, K_T, is defined by a line which is shifted upwards by a constant amount from the corresponding open-water line. The shift shows no dependence on ice thickness, and therefore appears to be caused by a discrete change in propeller operating regimes associated with increased propeller loads.

- The constant value of K_Q makes it inappropriate as a parameter for use in calculating a meaningful wake fraction. The shift in the K_T line shows that K_T is a better indicator of change between propellers operating in ice and in open water. Therefore the shaft thrust identity method has been used as the basis for calculating propeller advance velocity in ice and wake fraction.

- The total quasi-propulsive efficiency, η_D has been found to be well behaved and to depend on both advance coefficient and ice thickness. A linear regression fit to the compound parameter, $J_s \cdot h/D$ is quite reasonable. However, a second degree polynomial fit gives a marginal improvement in correlation and allows a more intuitively satisfying interpretation. It describes an increase in efficiency with $J_s \cdot h/D$ up to a maximum, and then a subsequent decline. Although its extrapolation beyond the largest trials data points may be no more numerically accurate than the linear equation, it avoids the erroneous interpretation that efficiency continues to increase indefinitely.

- Model scale efficiency predictions based on urea ice at CRREL are in the same general range as the trials data. The CRREL prediction is about 30 percent lower than the expected η_D value for the few available data points which are grouped into a small range of low $J_s \cdot h/D$ values. In view of the uncertainty in friction and higher ice strength this correlation is reasonable. In addition to velocity and thickness, the scaling of friction and ice strength were identified as important considerations in extending the model scale data set. In view of the much better correlation of Arctec's saline ice resistance data as compared to CRREL's urea ice resistance data, it would be useful to conduct controlled tests in different model ice materials as a means of identifying operating regimes where each type is applicable.

- A breakdown of quasi-propulsive efficiency into hull efficiency, relative rotative efficiency and open-water efficiency components was carried out. The shaft thrust identity was employed in determining propulsion coefficients for ship propeller operation in ice. Relative rotative efficiency η_R, was found to follow a well defined relationship with advance coefficient; but showed no dependence on ice thickness. This is reasonable since calculated open-water torque is indirectly affected by variation of K_T with J_s by means of the thrust identity. The small ice thickness range makes its influence difficult to assess. Hull efficiency showed no trend with ice thickness and had a very large scatter. Although it was approximately constant with J_s, no correlation could be ascertained because of the scatter. Therefore, it is essential to independently study the two components of hull efficiency: $(1 - t)$ and $(1 - w)$. Each considered separately is well behaved; but in combination they become unstable as a result of different trends with J_s and h. This is particularly true when $w = 1$ and η_H becomes singular. Consequently it is difficult to ascribe meaning to η_H. However, numerically the product of the three components $\eta_o \eta_R \eta_H$ gives the correct value of quasi-propulsive efficiency, η_D, which varies with both J_s and h. Since η_o and η_R vary with J_s it is important to characterize the h variation in the thrust deduction part of η_H.

- The behaviour of thrust deduction outside of the range of the MOBILE BAY trials data is thought to depend strongly on the loading associated with the increased ice thickness, as well as the ice fragment sizes and masses which interact with the propeller. However, the amount and size distribution of ice passing through the propeller region is generally unknown. A physical mechanism is postulated for the trend in thrust deduction with ice thickness as follows: The primary cause of reduced thrust deduction with increased ice thickness is believed to be the reduced relative importance of hydrodynamic effects as compared to the rapid increase in ice resistance and thrust requirements associated with thicker ice and hence greater loading on the ship.

The hydrodynamic effects involve the flow around the stern. It is postulated that the propeller slipstream and its associated region of low pressure cause greater amounts of ice to be drawn into the propeller race than during towing at the same speed. This increases the drag and consequently the required thrust and therefore the thrust deduction. Ice milling likely contributes to this process. Larger ice masses are not drawn into the propeller slipstream, so thrust deduction decreases with increasing ice thickness. A maximum is reached near the thinnest ice tested. In yet thinner ice, small fragments are impacted or crushed and no longer cause an augmentation of drag, and therefore thrust deduction drops to an open-water overload value.

The above hypothesis remains very speculative without supportive trials data from an extended thickness range or from self-propulsion tests in pre-cut ice of various sizes.

- Another physical mechanism which may affect thrust deduction, is the constraining influence of the towline on bow motions. In thick ice this constraint could lead to increased towed resistance and therefore cause lowered thrust deduction. Although there was no indication that this effect has occurred, it would be useful to ensure that the resistance data has not been biased by the dynamics of the towing system. Numerical studies or physical modelling of the towing process would be a means of studying this problem.

- It has not been possible to further breakdown the efficiency into open-water, behind pulling, and ice components. This would require thrust data from overloaded model tests and accurate full-scale, open-water towed resistance data.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A: CONCLUSIONS

The successful completion of the test series and analysis described in this report leads to the following conclusions:

(1) Towed resistance tests in level ice are feasible given the combination of appropriate vessels, adequate instrumentation, extensive planning, and superior shiphandling.

(2) The quality and consistency of the data collected was very high. The standard deviations in the towed resistance data is relatively large, due to tow-line oscillations, but this does not results in a significant error because the oscillations are periodic. The error in the thrust and torque data points derived from the individual self-propelled tests is generally smaller than the spread between data points. However, the towing procedures may have permitted pressure relief in the ice as a result of the presence of the towing vessel's track, which may have influenced the resistance measurements and therefore the propulsive coefficients. There was not sufficient thrust data from comparable self-propulsion tests in both the presence and absence of pressure relief to resolve this concern; but it appears that its influence was small in this case.

(3) From analysis of the MOBILE BAY towed hull resistance data:

° For the empirical analytic models A to O, and equations A to E (Table 4.1-11) with ice resistance dependent on thickness squared, it was found that the best fits of the trials resistance data were obtained with dependence on velocity squared.

° An improved formulation for empirical resistance prediction based on these results has been developed. However it is recognized that this equation is based on limited thickness data and that there was not sufficient ice strength data to identify its influence.

(4) Comparison of the towed resistance results with Vance's KATMAI BAY Full Scale trials resistance prediction showed good agreement as a result of his choice of thrust deduction.

(5) Comparison of the towed resistance results with model tests in urea ice performed at CRREL indicated that this ice material leads to excessively large predictions.

Comparison of the towed resistance results with model tests in saline ice performed at Arctec showed better agreement. However this result disagrees with similar comparisons involving the M.V. ARCTIC and PIERRE RADISSON, and is possibly due to a fortuitous cancellation of errors, rather than accuracy of modelling in saline ice.

(6) Analysis of these resistance comparisons, and those with derived empirical prediction techniques, indicated the primary importance of properly selecting targets for ice and model properties; particularly:

- hull-ice friction; and
- ice strength

The effective hull-ice friction is thought to be closely linked to model ice density via buoyancy forces and hull-form geometry. Thickness and speed were found to be of lesser importance.

(7) Empirically derived prediction equations for ice resistance appear unduly sensitive to ice strength since there was no discernible dependence on flexural strength in the towed results at least over the small range tested. The critical dependence on the friction conditions in the tests from which the equations were derived is confirmed by these towed trials.

(8) The application of the linear and non-linear resistance prediction formulations in the analysis of self-propelled data produced equivalent trends in the variation of thrust deduction with ice thickness.

(9) Quasi-propulsive coefficient showed a strong correlation with advance coefficient and a weak dependence on ice thickness.

(10) Observed values of K_Q were found to approach a constant value corresponding to the open water bollard value. The corresponding values of K_T were much better behaved, showing a constant shift above the open water curve. Thus, the shaft thrust identity method was considered to be the only valid approach for the determination of propeller advance velocity in ice.

(11) Thrust deduction exhibited a strong correlation with ice thickness, but the limited range of ice thickness does not allow a valid extrapolation to the open water condition. It is believed that the correlation with ice thickness varies primarily from changes in the relative

importance of hydrodynamic effects as compared to ice loading effects. No correlation with ship advance velocity was noted for the small range of advance available in the present trials. Re-analyzed data from the KATMAI BAY trials, over a wider range of advance, did indicate a trend with advance coefficient.

(12) Derived values of effective wake fraction showed a strong dependence on ship advance coefficient. This follows an expected trend asymptotic to positive infinity at bollard conditions and approaching a constant value at large advance. Although the calculated wake fractions are very large compared to clear water values, they are in general agreement with the results of tests reported for other icebreaking vessels. However, the trend is different from that observed by other investigators for multiple screw vessels. It should be noted that the wake fraction results have been calculated by applying the shaft thrust identity method to open water propeller data, since no propeller overload data was available. Furthermore there has been no correlation for propeller-ice interaction effects in the present analysis of the thrust data. No dependence on thickness was observed, thus indicating a low sensitivity to propeller/ice interaction effects. The numerical values derived from the self-propelled tests at CRREL in urea ice were significantly lower, although the small number of points and lack of variation in ice thickness and strength during the model tests make conclusive comparisons difficult.

(13) Values of hull efficiency, η_H, derived using estimates of wake factor, (1-w), and thrust deduction factor, (1-t), exhibited a wide scatter; making identification of trends difficult. The scatter was primarily due to the singularity for the case where $w = 1$, as well as the fact that thrust deduction and wake are dependent on different parameters. As a result hull efficiency is not a useful parameter and therefore thrust deduction and effective wake must be assessed independently as a means of obtaining the performance characteristics of a particular vessel in ice.

(14) Relative rotative efficiency, η_r, was heavily dependent on advance coefficient with no apparent correlation with ice thickness. Values in excess of 100% were observed, but results from KATMAI BAY trials and the CRREL model tests showed reasonable agreement.

(15) In general the agreement between KATMAI BAY and MOBILE BAY trials self-propulsion data and for all derived propulsive coefficients are excellent. Although very limited data is available from the self-propelled model tests at CRREL, propulsive efficiency seemed reasonable. All other terms, however, showed poor agreement. In particular, wake fraction appears to be grossly under-predicted by model tests in the ice basin.

(16) The severity and frequency of encounters between the MOBILE BAY propeller and ice pieces were negligible at speeds less than 4 knots, but increased in significance at higher speeds. Based on limited number of torque results from the towed tests it appears that the severity of the interactions is less than that predicted by tests in model ice.

B: RECOMMENDATIONS

Based on these conclusions as well as the uncertainties which remain, the following recommendations have been formulated. They address analysis techniques, model testing procedures and methodology, and further studies to enhance understanding of the trends and uncertainties observed.

1. Analysis Techniques:

° Empirically derived, non-dimensional resistance prediction formulae are valid and should be used to provide preliminary resistance estimates. Care must be taken, however, in reviewing the applicability of the data set from which a particular form was derived.

° Non-dimensional analysis is only useful when a large enough variation of the principal variables exists in the data set.

° The shaft thrust identity method should be used when deriving resistance estimates from full scale trials and in evaluating performance of future designs using open-water propeller curves.

2. Model Test Procedures:

° Resistance tests in ice for new designs must include variation in all parameters which may vary during actual operation. Other parameters, such as friction, must be carefully modelled at realistic target values.

° The selection of ice modelling materials must be carefully reviewed on the basis of performance, as well as cost.

° Shaft thrust must be measured in self-propelled tests in order that the thrust identify method may be used in analysis.

° Propeller overload tests should be considered an essential component of all model test programs which are intended to assess propulsive performance.

° Motions while icebreaking should be measured to facilitate comparisons of data sets from test programs in different ice materials and at different scales.

3. **Future Studies:**

° Additional full scale trials of a 140-foot WTGB should be undertaken. These trials should include:

i. Towed resistance tests in ice, with emphasis on lower thickness and a greater speed range. The influence of pressure relief and snow cover should be further investigated.

ii. Self-propelled tests in ice with greater variation in advance coefficient. These tests should once again be conducted in pressure relief conditions which are consistent with the towed resistance tests. A corresponding series of self-propulsion trials should be carried out in the same ice and ship operating conditions, but at different confinement conditions to allow a systematic assessment of the influence of pressure relief.

iii. Towed resistance, bollard, tow-rope pull, and free route tests in open water.

The purpose of these additional trials is the enhancement of the current valuable data base and the creation of a complete full scale characterization of vessel performance for at least one icebreaker.

° Towed resistance and self-propelled trials of another icebreaker, preferably a multiple screw ship would permit investigation of differences in propulsion parameters in ice due to variations in hull geometry and size, as well as propulsion configuration.

° Ice model tests of the 140′ WTGB form should be conducted in other available ice modelling materials. These tests must include both resistance and self-propelled tests with the aim of providing definitive judgments on the suitability of these materials for either resistance or propulsion tests. The importance of crushing strength in scaling and the inter-relationship between effective friction factor, ice density and hull form geometry should be investigated.

° Tests in a channel should be conducted to investigate the effect of variations in the amount, size and properties of ice interacting with the propeller. The influence of ice density, crushing strength and other parameters should be considered.

° Physical modelling of the tow line system used in these trials is necessary to investigate the effect of possible bow restraint and elastic behaviour of the tow system on resistance.

- Additional overload model tests of the 140' WTGB form in clear-water should be planned to determine the thrust performance parameter. This will allow comparison with proposed full scale trials, as well as allowing an interim determination of ice and over-propulsion effects separately from existing data.

6. REFERENCES

1. Froude, W., On Experiments with HMS GREYHOUND, TRINA, 1874.
2. Denny, Sir Maurice E., BSRA Resistance Experiments on the LUCY ASHTON, Part 1: Full-Scale Measurements, TRINA, 1951 (Part II, TRINA 1953).
3. Canham, H.J.S., Resistance, Propulsion, and Wake Tests with HMS PENELOPE, TRINA, 1974.
4. Herreshoff, H.C. and Newman, J.N., Full Scale Tank Tests of the 5.5-Meter Yacht ANTIOPE, SNAME T&R Bulletin 1-28, 1967.
5. Kuhn, John C., A Semi-Empirical Approach to Using Five Hole Pilot Tubes, Twenty First ATTC, 1986.
6. Tatinclaux, J.C., Effects of Ice Piece Size on Propller Torque in Ship-Model Tests, Twenty-First ATTC, 1986.
7. Vance, G.P., Analysis of the Performance of a 140' Great Lakes Icebreaker: USCGC KATMAI BAY, CRREL Report 80-8, 1980.
8. Bolin, P.G., The Ice Resistance Diagram as an Indication of Icebreaking Qualities of Sea Ships.
9. Tatinclaux, J.C., Model Tests on Two Models of 140' WTGB Icebreakers, CRREL Report 84-3, 1984.
10. Tatinclaux, J.C., Propulsion Tests in Level Ice on a Model of a 140-foot WTGB Icebreaker, CRREL Report 85-4, 1985.
11. LeCourt, E.J., Icebreaking Model Tests of the 140-foot WYTM, ARCTEC Report 202C-2, 1974.
12. West, EE, Powering Predictions for the USCG 140-foot WYTM Represented by Model 5336, NSRDC Report SPD-233-16, 1975.
13. Vance, G.P., A Scaling System for Vessels in Ice, SNAME Ice Tech Symposium, Montreal, 1975.
14. Lewis, J.W.; DeBord, F.W; and Bulat, V.A., Resistance and Propulsion of Iceworthy Ships, SNAME Trans., Vol. 90, 1982.
15. Edwards, R.Y; Lewis, J.W.; Wheaton, J.W.; and Coburn, J.L., Full-Scale and Model Tests of a Great Lakes Icebreaker, SNAME Trans., Vol. 80, 1972.

16. Murdey, D.C., Resistance and Propulsion Experiments with Model 327-1 and Propellers 66C and 66R, National Research Council MDSL Report LTR-SH-269, 1980.

17. DeBord, F.W., Voelker, R.P., Geisel, F.A., Coburn, J.L., and Dane, K.E., Winter 1981 Trafficability Tests of the USCGC POLAR SEA; Volume V - Bollard and Tow-Rope Pull Tests, ARCTEC Incorporated Report 583C-3, Columbia, MD 1981.

18. Zahn, P.Z., Preliminary Test Plan for Towed Resistance Tests in Ice of the 140' WTGB MOBILE BAY, ARCTEC Report 1252C-1, 1986.

19. Tatinclaux, J.C., Effect of Ice-Floe Size on Propeller Torque in Ship-Model Tests, Presented at 21st ATTC, Washington, D.C., 1986.

20. Abdelnour R., Mathews S., Howard D., El-Tahan H., Factors Influencing the Entrainment and Impact of Ice Pieces with a Vessel's Propeller, Arctec Newfoundland Report 93C, Submitted to TDC, 1986.

21. Enkvist E., and Makinen S., A Fine Grain Model Ice, Proc. IAHR, Vol. II, Hamburg, 1984.

22. Timco G.W., EG/AD/S: A New Type of Model Ice for Refrigerated Towing Tanks, Cold Regions Science and Technology, 12, 1986.

23. Timco, G.W., Frederking. R.M.W., Confined Compression Tests: Outlining the Failure Envelope of Columnar Sea Ice, Cold REgions Science and Technology, 12, 1986.

24. Reinicke, K.M., Ralston, T.d., Plastic Limit Analysis with an Anistropic, Parabolic Yield Function, Int. J. Rock Mech. Mining Science and Geomech. Abstract, 14, 1977.

25. Atkins, A.J., Icebreaker Modelling, J. Ship Research, 19, 1975.

26. Phillips, L.D., Daley, C.G., McCallum J.S., Dynamic Ship/Ice Impact-Parametric Physical Modelling, Presented Mari-Tech 86, Vancouver, 1986.

27. Free, A., Ice Model Tests of U.S. Coast Guard Replacement Icebreaker, A.E.I. Report 1209C

28. McKindra, C.D., Lutton, T.C., Statistical Analysis of Broken Ice Dimensions Generated During 140 foot WTGB Icebreaking Trials, Proc. POAC 81, Vol.I, 1981.

29. Major, R.A., Clearing Ice from Navigation Channels on the Great Lakes - St. Lawrence Seaway System, Technical Note, Arctec Report 463, 1978.

30. Tatinclaux, J.C., Level Icebreaking by a Simple Wedge, CRREL Report 85-22.

31. Glen, I.F., Graham, B., Howard, D., Comfort, G.C., and Yau, G., Modelling the Broken Channel; (Submitted by Arctec and Dome Petroleum to the Canadain Coast Guard) ACL report 1519C, 1984.

Volume

2

TP 8487E

Towed Resistance Trials In Ice Of The USCGC Mobile Bay (WTGB 103)

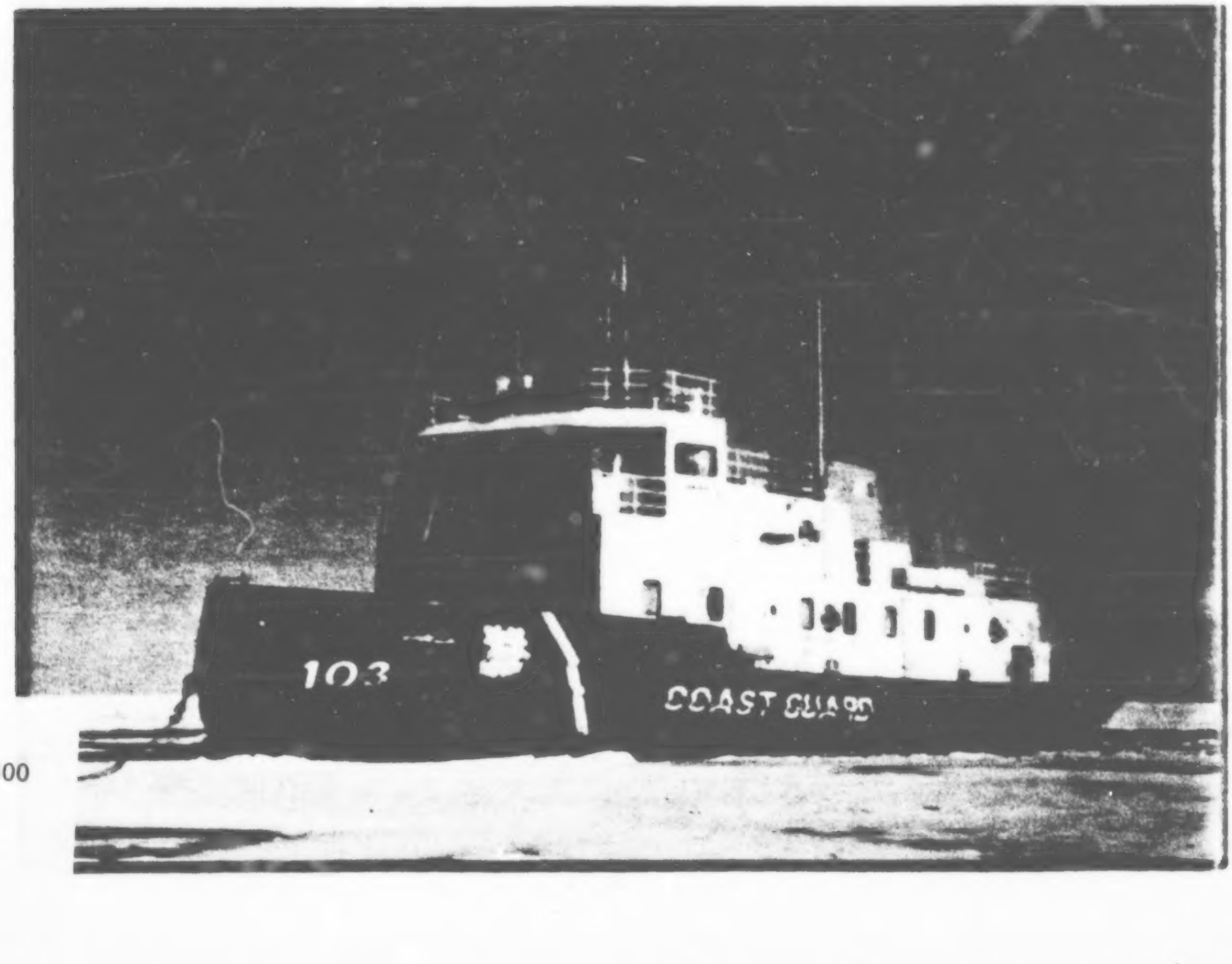
Volume 2: Appendices
September 1986

Transport Canada
Development

Transports Canada
Developpement

U.S. COAST GUARD
ENGINEERING

U.S. DEPARTMENT OF TRANSPORTATION
MARITIME ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT



CA1
DTC 800
86
T56
v.2
c.2

CA1
DTC 800
86
T56
V.
C.

ARCTEC CANADA LIMITED

FR 1923E
TP 8487E

TOWED RESISTANCE TRIALS IN ICE OF THE USCGC MOBILE BAY (WTGB103)

VOLUME 2 - APPENDICES

By:

L. PHILLIPS
P. ZAHN

Library and Information Centre /
Centre de Documentation (GSLA)
RECEIVED - RECU LE
APR 26 1988
Transport Canada / Transports Canada

SEPTEMBER 1986

SUBMITTED TO:

Transportation Development Centre,
Guy Favreau Complex,
200 Dorchester Blvd. West,
Suite 601, West Tower,
Montreal, Quebec.
H2Z 1X4

SUBMITTED BY:

ARCTEC CANADA LIMITED
311 Legget Drive,
Kanata, Ontario.
K2K 1Z8

379537

PROJECT TEAM CONSISTED OF:

ARCTEC CANADA LIMITED and ARCTEC ENGINEERING INC.

ARCTEC CANADA LIMITED:

I. F. GLEN
L. D. PHILLIPS
D. FRERE

ARCTEC ENGINEERING INC.:

J.L. COBURN
P. ZAHN

with technical assistance from:

T. JOHNSTONE
A. LEMIEUX

and others.

Un sommaire en français de ce document est inclus dans le volume I.

THE CONTENTS OF THIS REPORT REFLECT THE VIEWS OF THE CONTRACTOR AND NOT NECESSARILY THE OFFICIAL VIEWS OF THE TRANSPORTATION DEVELOPMENT CENTRE.

APPROVED BY ______________________
IAN F. GLEN, PRESIDENT.

Transport Canada Transports Canada

Development Développement

REPORT DOCUMENTATION FORM

1. Transport Canada Report No.
TP 8487E

2. TDC Project No.
6481/6482/6483

3. Recipient's Catalogue No.

4. Title and Subtitle
Towed Resistance Trials in Ice of the USCGC Mobile Bay (WTGB103)

5. Report Date
September 1986

6. Performing Organization Report No.
1923E

7. Author(s)
L.D. Phillips, P.Z. Zahn

8. Transport Canada File No.
D1460-181-3

9. Performing Organization Name and Address
Arctec Canada Limited
311 Legget Drive
Kanata, Ontario
K2K 1Z8

10. DSS File No.
11SD.T8200-5-5531

11. DSS or Transport Canada Contract No.
0SD85-00142

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
200 Dorchester Blvd. West
Suite 601, West Tower
Montreal, Quebec H2Z 1X4

13. Type of Report and Period Covered
Final

14. Sponsoring Agency Code

15. Supplementary Notes
Volume 1 - Final Report
Volume 2 - Appendices

16. TDC Project Officer
I.M. Bayly

17. Abstract

This report presents the methodology and results of a joint Canadian and American program of full scale towed resistance trials, and represents a major milestone in the ability to predict the operational performance of ships in ice. An extensive series of towed resistance tests and corresponding self-propulsion tests involving the USCGC MOBILE BAY were carried out under the auspices of the Arctic Ship Trafficability Program. The trials have provided the first full scale verification of icebreaker resistance. Testing was carried out in Lake Michigan at various speeds and in a range of thicknesses of level, unbroken ice. Thrust, torque, propeller RPM, speed and towing pull were recorded. The results have been compared to established ice resistance formulations to assess the influence of different test parameters. An improved empirical resistance prediction equation has been derived. Trends in thrust deduction, wake fraction and propulsive efficiency components have been examined and compared to model test results for the 140' WTGB class hull form. The correlation between full scale test data and model scale predictions has been assessed. Recommendations are presented which affect design procedures and ice basin test methods for assessing propulsive performance of icebreaking ships.

18. Key Words
Full scale trials, resistance, performance prediction, icebreakers

19. Distribution Statement
Limited number of copies are available from the Transportation Development Centre.

20. Security Classification (of this report)
Unclassified

21. Security Classification (of this page)
Unclassified

22. No. of Pages
339

23. Price
Nil

TDC/CDT 79-005
Rev 86

Canada

Transports Canada Transport Canada
Développement Development

FORMULE DOCUMENTAIRE DU RAPPORT

1. Nº du rapport Transports Canada
TP 8487E

2. Nº de l'étude — CDT
6481/6482/6483

3. Nº de catalogue du destinataire

4. Titre et sous-titre
Towed Resistance Trials in Ice of the USCGC Mobile Bay (WTGB103)

5. Date du rapport
Septembre 1986

6. Nº du rapport de l'organisme exécutant
1923E

7. Auteur(s)
L.D. Phillips, P.Z. Zahn

8. Nº de dossier Transports Canada
D 1460-181-3

9. Nom et adresse de l'organisme exécutant
Arctec Canada Limited
311 Legget Drive
Kanata, Ontario
K2K 1Z8

10. Nº de dossier — ASC
11SD.T8200-5-5531

11. Nº de contrat — ASC ou Transports Canada
0SD85-00142

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
200 ouest, boul. Dorchester
Suite 601, tour ouest
Montréal (Québec) H2Z 1X4

13. Genre de rapport et période visée
Final

14. Code de l'organisme parrain

15. Remarques additionnelles
Volume 1 - Rapport final
Volume 2 - Annexes

16. Agent de projet — CDT
I.M. Bayly

17. Résumé
Ce rapport présente le mode opératoire et les résultats des essais de résistance à l'avancement d'un navire réel remorqué, le USCCG MOBILE BAY. Faits dans le cadre d'un programme conjoint canado-américain, désigné Arctic Ship Trafficability Program, ces essais constituent un jalon important dans l'évolution des techniques de prévision des performances réelles des navires dans les glaces. Ils ont été réalisés, aussi bien les essais de traction que les essais d'autopropulsion correspondants, dans le lac Michigan à diverses vitesses et dans diverses épaisseurs de glace uniforme et intacte. C'était la première fois que l'on vérifiait en vraie grandeur la résistance à la marche d'un brise-glace. Les paramètres mesurés ont été la poussée, le couple, le régime de rotation de l'hélice, la vitesse et l'effort de traction. Par la suite, les résultats ont été comparés aux valeurs théoriques dérivées d'équations établies de résistance des glaces en vue d'évaluer l'influence des différents paramètres d'essai. Cet exercice a débouché sur une équation empirique de résistance des glaces à l'avancement qui serre la réalité de plus près. Les chercheurs ont suivi l'évolution des coefficients de succion et de sillage ainsi que du rendement propulsif global, et ils les ont comparés aux résultats d'essais sur modèle réduit d'une coque d'une classe WTGB de 140 pieds de longueur. Ils ont également recherché la corrélation existant entre les résultats des essais en vraie grandeur et les prévisions tirées des essais en bassin. Le rapport se termine par des recommandations qui influenceront les techniques de conception des brise-glace et les méthodes de détermination de leur rendement propulsif à partir d'essais en bassin des glaces.

18. Mots-clés
Essai en vraie grandeur, résistance à la marche, prévision des performances, Brise-glace.

19. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

20. Classification de sécurité (de ce rapport)	21. Classification de sécurité (de cette page)	22. Nombre de pages	23. Prix
non classifié	non classifiée	339	Aucun

Canada

TABLE OF CONTENTS

VOLUME II - APPENDICES

APPENDIX (i) WORK STATEMENT - TASK GROUP D........................1 - 5
APPENDIX A - IMPLICATIONS FOR MODEL TEST METHODS..................1 - 8
APPENDIX B - SHIP TRACKINGS FOR TOWED AND SELF-PROPELLED TESTS...1 - 17
APPENDIX C - TOWED TEST RESULTS..................................1 - 88
APPENDIX D - SELF-PROPELLED TEST RESULTS AND ANALYSIS............1 - 145
APPENDIX E - REGRESSIONS FOR LEVEL ICE RESISTANCE EQUATIONS......1 - 59
APPENDIX F - TEST INSTRUMENTATION................................1 - 11

NOTE ON UNITS:

This study has been carried out jointly with the U.S. Maritime Administration and therefore Imperial units have been used in data collection and reduction. This edition of the report complies with the Transport Canada requirements for presentation of results in terms of S.I. units. All Tables and Figures have been converted to S.I. units and data in the text has been duplicated in both systems. However, some figures and appendices which show typical data in its computer generated form retain Imperial units and therefore the following set of conversions is provided:

Length (metres)	1 m = 39.36 inches
Force (Newtons)	1 N = 0.2248 lb_f
Stress (kilo Pascals)	1 kPa = 0.145 psi
Power (kilo Watts)	1 kW = 1.341 Hp
Speed (knots)	1 kts = 0.515 m/s = 1.689 ft/s

APPENDIX (i)

WORK STATEMENT: TASK GROUP D

Departures from Task Specifications:

The contractual obligations under which Arctec Canada Limited has contributed to the MOBILE BAY study are listed in this appendix. Within the constraints of the overall test program it has been possible to fulfill the majority of the primary objectives. However, there are three departures from the task specifications which warrant specific comment.

(i) Task D1, Section 5.11.1 specified an examination of the influence of snow coverage on the measured towed resistance. (Alsc Section 5.11.1 Task 3). Equipment and procedures were assembled to permit snow clearing during selected trials. However, it was found in the trials region that there was insufficient snow on the ice to conduct these tests. Snow coverage was less than that usually remaining after snow blowing equipment is used. Hence it was not possible to study the influence of snow cover in the analysis phase of the work. Recommendation for its inclusion in follow-up trials have been included.

(ii) Task D2, Section 5.11.2 called for a method of identifying and recording ice fracture modes and broken piece sizes. An attempt was made to assess the broken channel characteristics by means of a video camera mounted on the bow and stern of the MOBILE BAY. Unfortunately this video data was limited and did not prove to be of acceptable quality for reporting.

(iii) Investigation of the frequency and severity of propeller-ice interactions for MOBILE BAY is included in Task D2, Section 5.11.2. The instrumentation system developed for the trials incorporated a number of features to improve the quality of the test data for the purpose of assessing the level of propeller-ice interactions. In particular an analogue tape recorder was added to collect raw, unfiltered data during selected tests. The raw data was subsequently examined visually and also digitized at a high sampling rate and at a high filter frequency as compared to that of the onboard analysis system. It was found that the torque results were substantially the same between the raw data and the filtered data, ignoring spurious transmission spikes.

At low RPM the thrust data was more sensitive to the ice encounters than the torque. Hence the thrust data from the towed tests has been tabulated as a means of assessing the extent of propeller-ice interaction. General observations concerning the frequency and severity of ice interactions as a function of velocity have been derived from these towed thrust results and are applied to the discussion of self-propelled thrust. However, it has not been feasible to modify wake fraction results on the basis of the 'zero thrust' RPM in the absence of both overload propeller open water curves and full scale, clear-water towed resistance data.

Several areas of the work have received extended attention where it was considered important to clarify the basic test results and their implications. A significant effort was made towards obtaining the maximum number of rigorous ice property measurements. The trials matrix of towed and self-propelled tests was expanded as much as innovation could make possible within the time frame available, and the analysis of results (Task D4) is very comprehensive. The implications of the trials data to model test prediction of ice resistance have been pursued thoroughly.

TITLE: **Study on Measurement of Global Ice Impact Loads in the Alaskan Beaufort Sea.** Towed Resistance Trials of MOBILE BAY.

Under "Statement of Work" on page 1 of contract:

Delete entirely

Substitute therefore:

STATEMENT OF WORK:

You shall carry out the work specified in Appendix "A" (section 5.9 excluded) attached hereto and forming part of this contract along with the following work:

The numbering for "Preparation of Final Report and Progress Reports" is changed from 5.11 to 5.12

5.11 Towed Resistance and Propulsion Tests Task Group D

Towed resistance and propulsion testing is to be carried out at full-scale using a suitably matched pair of icebreaking vessels in a convenient location where there is uniform level ice.

This project is jointly sponsored by the US Maritime Administration and US Coastguard along with the Transportation Development Centre, and is to be jointly executed by the contractor acting in accordance with this contract and Arctec Engineering Ltd. under contract to the US Government. The tasks outlined in the following paragraphs are to be subdivided into elements which can be carried out individually and integrated into an effective whole, the total amount to be done under this contract is limited by the price ceiling given in the Proposal or as subsequently negotiated.

The following tasks, prefixed "D" relate to task numbers used in the Arctec proposal on this subject.

5.11.1 Planning & Software - Task D1

Test plans are to be developed in further detail in conjunction with detailed design of the instrumentation system as outlined in section (8). Software is also to be prepared for collection and analysis of the test data.

In addition to items already proposed, planning is to consider methods for removal from sections of the ship's intended track of any significant quantity of snow which may be present on the ice. This is to make possible an adequate comparison with model tests, for which snow cover cannot be effectively modelled. It will also enable comparison of resistance with and without snow cover, in ice which is otherwise nearly identical.

5.11.2 Prepare Instrumentation and Support Equipment - Task D2

The instrumentation system is to measure with a high degree of accuracy all parameters pertinent to the measurement of towed resistance, of thrust deduction and wake where self-propulsion is involved, and of the ice conditions at the time of testing.

Particular consideration is to be given to the following:

a) As it is intended to turn the propeller at a rate which will give zero thrust or drag, it is important that the thrust measurement system be sensitive and accurate at zero thrust, or some other means of detecting the zero thrust condition will have to be devised and provided. Shaft rotation speed should also be accurately recorded in the zero thrust condition, as it will provide a good measure of the wake and wake fraction through the propeller disc. Any water current under the ice will also have an important influence, and is to be detected and measured.

b) Equipment for removal of snow from segments of the intended test track is to be provided.

c) A power-driven hydraulic pump, for use with the cantilever ice beam is to be provided, in order that the strain rate may be effectively controlled. A means of measuring or estimating strain rate is to be provided.

d) A method of identifying and recording ice fracture modes, patterns, and broken piece sizes is to be provided.

e) A means of measuring speed through the ice, other than the doppler radar, should be provided in addition, in order to verify the doppler readings, particularly at low speeds.

f) Provision is to be made for detecting and recording the frequency and severity of propeller/ice interactions which occur during testing.

g) Propeller RPM measurement should be highly accurate and sensitive to short-term variations due to propeller/ice interactions.

Final details of the instrumentation system including particularly the ice properties measurement arrangements, are to be reviewed with Mr. S. Jones of the Institute of Marine Dynamics, who will advise the Scientific Authority as to their adequacy.

5.11.3 Install Instrumentation and Conduct Tests - Task D3

Instrumentation is to be installed in a manner such as to foster reliable functioning and effective use.

Instrumentation and equipment specifically mentioned in the preceeding tasks are to be installed and the related measurements carried out during testing, unless prevented by unavoidable circumstances. Measurement of resistance in snow-free ice is considered to be particularly important.

Ice properties are to be measured (by means of temperature profiles) in snow-free and snow-covered ice in a manner to enable detection of any differences which may exist. This is to be done when ice is freshly exposed, and after a period of time (such as overnight) when the bare ice has been directly exposed to freezing air temperatures. Ice properties are to be measured close to the tests, both in space and time, to the extent feasible, or until it is well established that there is negligible variation.

In order that comparison of resistance with snow cover, with model test results may be attempted, comparative testing with and without snow cover is to be carried out, to specifically measure the effect of the snow cover.

It is suggested that the towing icebreaker pre-break a channel before towing, in order to avoid an uneven pull on the towline.

Drafts of the test vessel are to be read and recorded twice daily and immediately if liquids are transferred during a day of testing.

5.11.4 Data Analysis - Task D4

Analysis is to include a full and thorough examination of all parameters, the accuracy of all measurements is to be determined and defined, estimates being provided where better data is not obtainable. An estimate of the sensitivity of the output results of the analysis, to likely inaccuracies in the inputs is to be made and reported.

5.11.5 Reporting - Task D5

The report is to be as proposed, and in accordance with TP929 and other requirements of this work statement.

APPENDIX A

IMPLICATIONS FOR MODEL TEST METHODS

IMPLICATIONS FOR MODEL TEST METHODS

It is generally agreed that predictions of performance based on model tests result in an over estimation of the power requirements for ships operating in level ice, unless an empirical scaling factor is introduced. The comparison between the towed resistance and model scale resistance in Section 4.1 and between full scale self-propulsion trials and model tests in section 4.2, has indicated that significant modelling problems exist in both areas. While it must be concluded that there is insufficient data to determine the nature and interdependence of the factors influencing resistance and propulsion in ice; there is circumstantial evidence which suggests that certain fundamental ice modelling concepts may require modification.

The ratio of elastic modulus to flexural strength, E/σ_f has evolved as the principal indicator of the extent to which a synthetic ice material represents the mechanical behaviour of a full scale ice sheet. However, comparison of model predictions to the results of the MOBILE BAY towed resistance trials have indicated that this approach may be too simplistic and leads to significant modelling distortions. It was expected that tests in urea ice would show a better correlation to the full scale trials than saline ice tests, because the former has a higher E/σ_f ratio. This was not observed. The urea ice provided a significant over prediction of ice resistance, while the saline ice tests resulted in a better approximation.

In the correlation of propulsion results the urea ice test data was found to provide inaccurate estimates of both thrust deduction and wake fraction. No saline ice data was available for comparison.

It is the aim of this section to account for the discrepancies between full scale and model scale results and to provide some insights on improving ice model test methods. The following discussion includes:

- Summary of the recent developments in ice modelling criteria and materials

- Review of conceptual basis of physical modelling,

- Requirement for changes in modelling criteria as a result of MOBILE BAY trials; and an evaluation of the influence of different physical parameters; and

- Assessment of advantages and shortcomings of different ice materials.

Summary of Recent Developments in Ice Modelling: Criteria and Materials

Modelling materials for ship performance testing in ice have evolved to better replicate sea ice failure mechanics. In the earliest testing the model ice was produced by freezing an aqueous solution of salt. This ice material was known as saline ice. It did not prove satisfactory because the elastic strain modulus, E, was too low and the ice exhibited large plastic deformations during icebreaking. This was ascribed to a low E/σ_f ratio. A significant improvement in this ratio was achieved by the replacement of salt with a carbamide dopant. This resulted in the urea type ice; which is columnar in crystal structure with a mechanically strong upper layer, a thin transition layer, and a weak lower layer. A fine-grained saline model ice known as WARC ice was developed by Enkvist and Makinen [21] in 1984. It is produced by continuously spraying a sodium chloride solution throughout the growth cycle. Its granular structure results in a more realistic E/σ_f ratio, but there is some concern that it does not scale correctly in uniaxial compressive strength or confined compressive strength.

Timco [22] has recently developed a new type of model ice for refrigerated towing tanks, known as EG/AD/S ice. This abbreviation refers to the ethylene glycol, aliphatic detergent, and sugar which are added to produce its characteristic mechanical behaviour. Timco reports that EG/AD/S ice properties are superior to urea type ice in many respects and results in a better replication of sea ice behaviour. However, the E/σ_f ratio is about the same as for urea ice.

MOD-ICE is a wax-type model ice which is extensively used at Arctec. It is a homogeneous and brittle solid which is capable of much higher E/σ_f ratios and therefore exhibits excellent piece size distribution. MOD-ICE is not a refrigerated ice and therefore does not have the columnar crystal structure of ice in full scale. Rather it replicates the mechanical properties associated with the failure process, such as E, σ_f, σ_c, etc. In this respect it appears similar to the WARC ice with its fine granular structure.

It is not unexpected that all of these model ice materials fall short of being perfect replicas of fresh water ice or sea ice, because of the complexity and variability of the material which is being scaled. Work is continuing in many areas to define the pertinent characteristics of ice at full scale and to reproduce these properties at model scale. Of particular note is the work by Timco [22] and Frederking [23] on improved fracture toughness properties in EG/AD/S ice and the importance of failure envelopes to describe stress levels at which ice yields for any combination of compression or tensile stress states. This provides a basis for the use of plasticity theory to analyze problems in ice mechanics [24], which agrees conceptually with the physical modelling approach recommended by Atkins [25].

Review of Physical Modelling Concepts

Physical modelling of fresh water ice or sea ice has evolved towards a treatment of icebreaking as a fracturing of a brittle material. Atkins [25] introduced the concept of fracture toughness in 1975 as part of a rigorous derivation of scaling relationships for ice. Fracture toughness, R, expresses the resistance of a brittle material to propagation of cracks in terms of loading to displacement ratio and cracking force. Atkins discouraged the use of flexural strength, σ_f as a measure of ice properties since it does not uniquely represent brittle failure. Instead he utilized fracture toughness to describe ice sheet flexure: compliant ice sheets corresponding to small loading to displacement ratios; and stiff sheets having large loading to displacement ratios. The usual scaling relationship for ice strength could be derived by assuming that the gravitational and cracking forces are the governing influences which must be preserved in balance during scaling. This expression gives:

$$\sigma_{fm} = \frac{1}{\lambda} \frac{\rho_m}{\rho_p} \sigma_{fp} \tag{5.1}$$

which shows a linear dependence on geometric scale factor λ and a correction for the difference in density.

A similar application of similitude arguments to inertia and cracking forces resulted in the definition of an ice number:

$$I_n = \frac{V^2 \rho \sqrt{L}}{K} \tag{5.2}$$

where $K_I = \sqrt{ER}$ is a stress intensity factor, which includes both elastic modulus and fracture toughness. It was thought that the unrealistic plasticity of the model ice sheets could be improved by selecting a material which allows proper scaling of ice number. This corresponds to a design equation for scaling ice flexural strength of the form:

$$\sigma_p = \lambda^{-1/2} \frac{K_p}{K_m} \sigma_m \tag{5.3}$$

Requirement for Changes in Model Test Materials

Crushing Strength

Results reported by Phillips [26] from M.V.ARCTIC parametric model tests have indicated that uniaxial ice strength scaling is subject to a pressure-area type of relationship which may be associated with differences in flow propagation at model scale and full scale. Therefore a corollary to Atkin's analysis may be postulated, which applies the stress intensity factor argument to indentation (crushing) strength.

This leads to a modified scaling relationship in which indentation (crushing) strengths are severely reduced as compared to the usual geometric scaling. Although the weak dependence of force on ice crushing strength moderates this crushing strength scale effect somewhat, it would be expected that the more easily crushed ice would translate into reduced breaking resistance and reduced secondary crushing resistance along the model's sideshell.

This effect may explain why the saline ice tests were in better agreement with the towed resistance data than the urea ice tests. The urea ice has a higher elastic modulus, E, which improves the stiffness and therefore results in higher crushing forces, greater inertia forces, and higher effective flexural forces (through increased strain rates). The saline ice appears to have two modelling errors that cancel: an excessive crushing strength and an excessively compliant elastic strain modulus. Urea ice has an improved elastic modulus, and therefore the errors are no longer in balance and the predicted resistance becomes very large.

The ratio of crushing strength to flexural strength in fresh water ice or sea ice is approximately 4:1. Saline and urea type ice have ratios in excess of this. In MOD-ICE the ratio is close to 1:1. If the sea ice crushing strength does scale according to a pressure-area relationship, then the target model scale ratio σ_c/σ_f may be a function of scaling ratio, λ, and could be 1:1 or less. This suggests that MOD-ICE has both an improved E/σ_f ratio and a reduced σ_c and therefore a better correlation to full scale towed resistance data. A recent test program in MOD-ICE for the U.S. Coast Guard replacement icebreaker by Free [27] has strengthened this conjecture, since those resistance results were in excellent agreement with Lewis' general resistance form, which in turn is a reasonable fit to the MOBILE BAY data.

Density and Friction Coefficient

Another parameter which has a significant affect on model scale resistance is density or its equivalent specific gravity. Urea ice and saline ice both have specific gravities of approximately 0.94 relative to fresh water. MOD-ICE has a value of 0.88. The equivalent specific gravity of sea ice is C.90. This means that urea and saline ice materials are relatively less buoyant than sea ice and will not rise up as quickly once submerged under the hull. The effective hull-ice friction coefficient is reduced, but the trajectory of the ice along the hull is extended. In this respect, it has been observed from the analysis of MOBILE BAY resistance results that model test predictions are extremely sensitive to the hull-ice friction and therefore density effects could translate into large changes in resistance. This scale effect is further complicated in the case of the saline ice by the compliance of the sheet, which results in large broken fragments under the hull. The converse situation occurs for icebreaking in MOD-ICE sheets: the effective friction coefficient is marginally increased by the larger buoyancy forces and fragments ride up more quickly. This may result in more realistic side shell crushing loads and reduced friction resistance along the under side of the hull and stern.

Ice Piece Size Distribution

A statistical analysis of the broken ice dimensions generated during the KATMAI BAY trials has been reported by McKindra and Lutton [28]. They describe a sequence of piece size formation which includes:

1. Radial cracking at the bow,
2. Single or multiple rows of circumferential cracks prior to failure,
3. Breakage of ice into four or more principal wedges; and subsequently,
4. Side cusp breakage along the side of the vessel.

The broken channel distribution is reported to be lognormal. Ice thickness was found to be the dominant parameter in determining ice dimensions, which also varied with ship velocity. Mean size was a function of the ratio of ice strength and water density.

Model scale tests of the 140 foot WTGB form in saline ice by Major [29] are reported to have showed statistics of the same order. A more detailed study by Tatinclaux [30] of a wedge bow segment in urea ice provided a piece size distribution which was lognormal and with a mean length equivalent to the full scale mean. Tatinclaux derives a different influence of ice thickness. However, the wedge bow segment does not introduce the secondary side shell crushing that would normally occur with a full model and therefore the urea ice mean value in the presence of a complete model would be smaller than in full scale.

Influence on Propulsive Factors

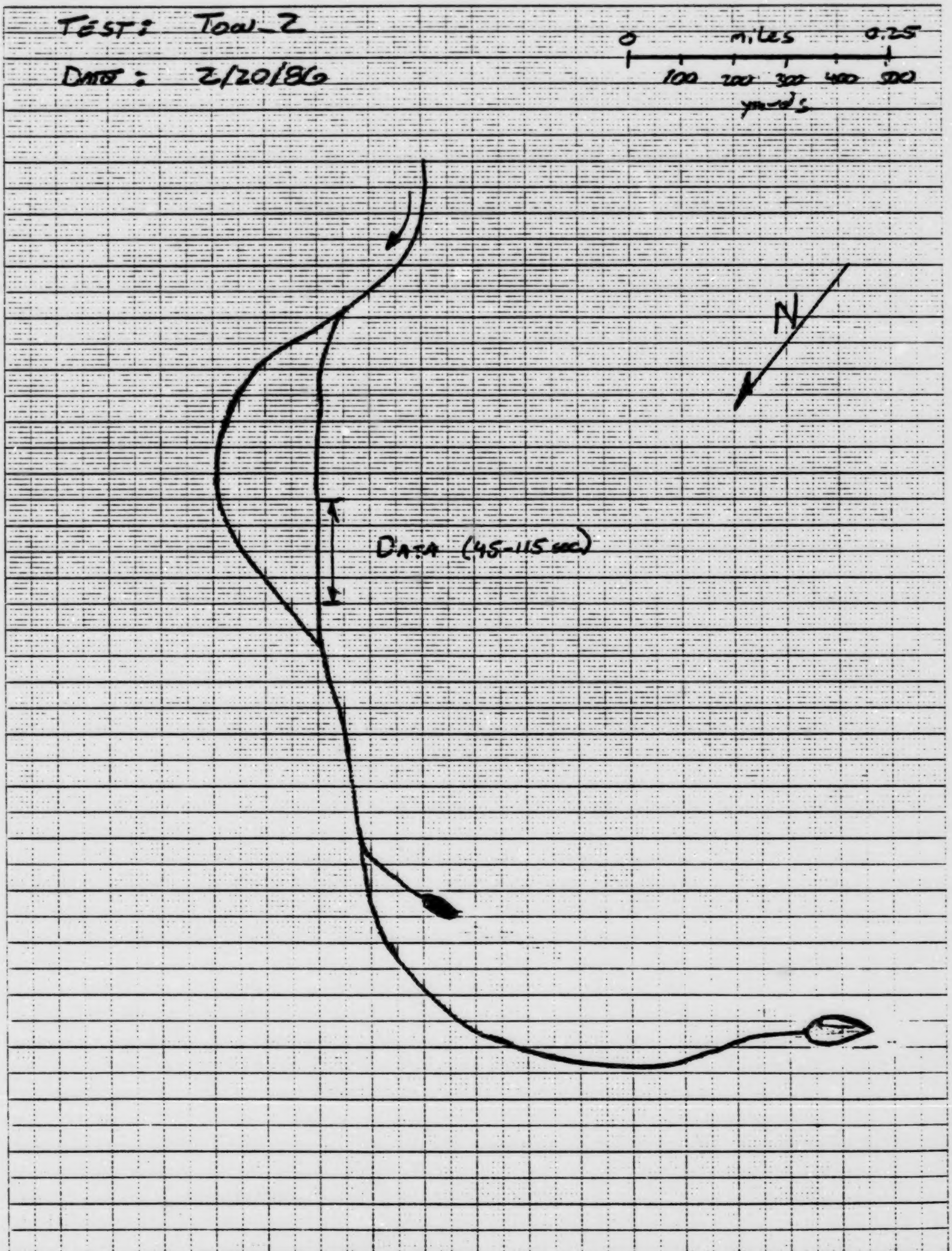
The study by Tatinclaux of the effect of piece size on propeller torque for the 140 foot WTGB model demonstrated a range of behaviour which is strongly dependent on dimensions of the ice reaching the propeller. The tests were valuable in defining upper bound trends for very large urea ice fragments entrained into the propeller race. However, the problem of assessing the piece-size distribution which the propeller will actually experience has not been addressed. The answer to this question appears to involve a resolution of the same questions of concern in the physical modelling of resistance; which for propulsion refer to:

- The crushing strength of the ice; which influences the size of pieces formed and affects impact response of the propeller.
- The density of the ice; which determines the buoyancy forces and therefore the amount of ice that reaches the propeller. It is suspected that variations in the hull-ice friction coefficient along the hull and with piece-size may significantly affect the amount of entrained ice.
- The piece size distribution at the propeller; which determines the relative extent of ice ingestion and milling which will occur.

APPENDIX B

SHIP TRACKLINES FOR TOWED AND SELF-PROPELLED TESTS

These plots were made as tracings off the radar screen of MOBILE BAY immediately following each test. They were used to confirm test configurations and give unique insight into the success of test procedures.



TEST: TOW_2

DATE: 2/20/86

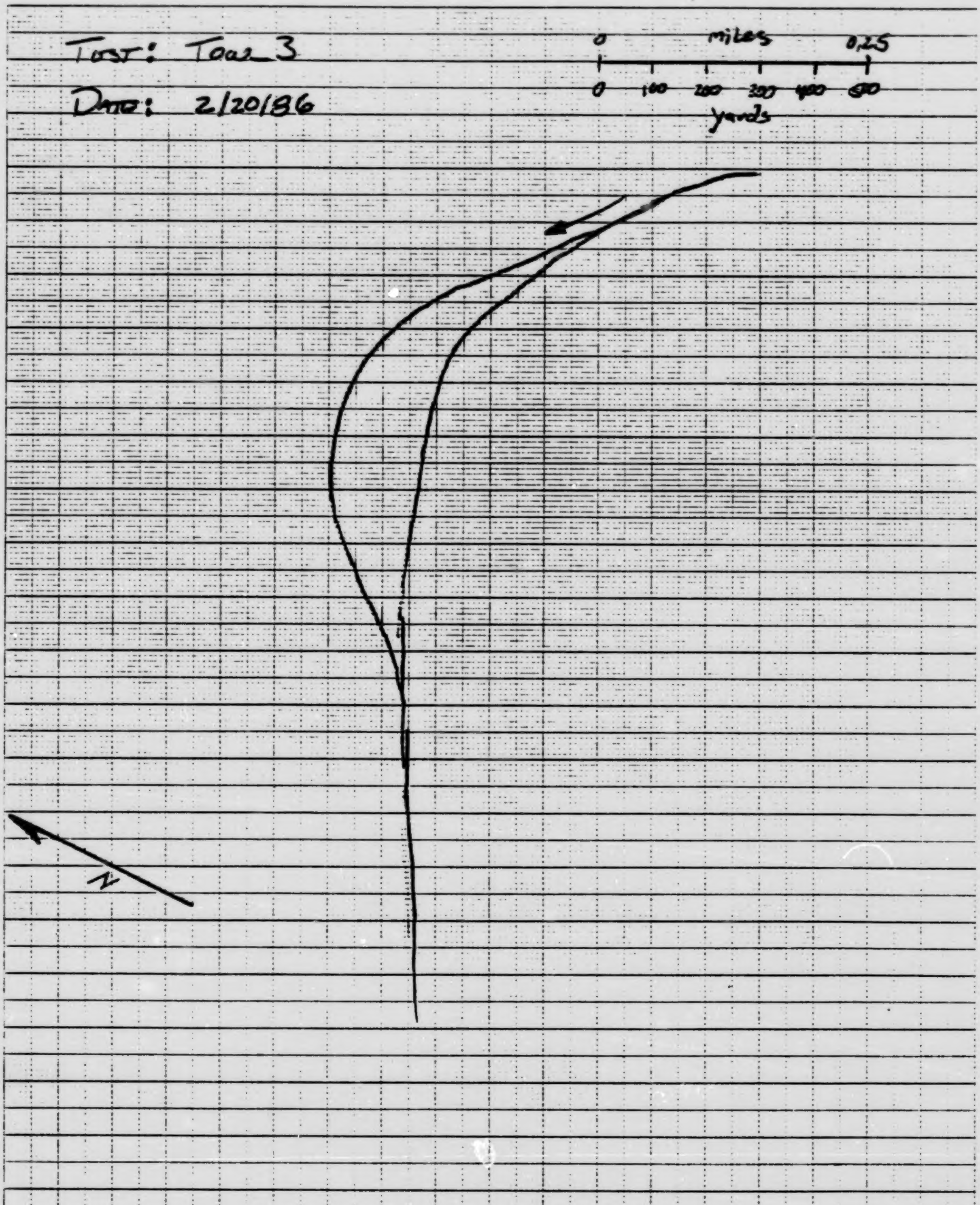
0 miles 0.25
100 200 300 400 500
yards
N
DATA (45-115 sec)

461510

K&E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

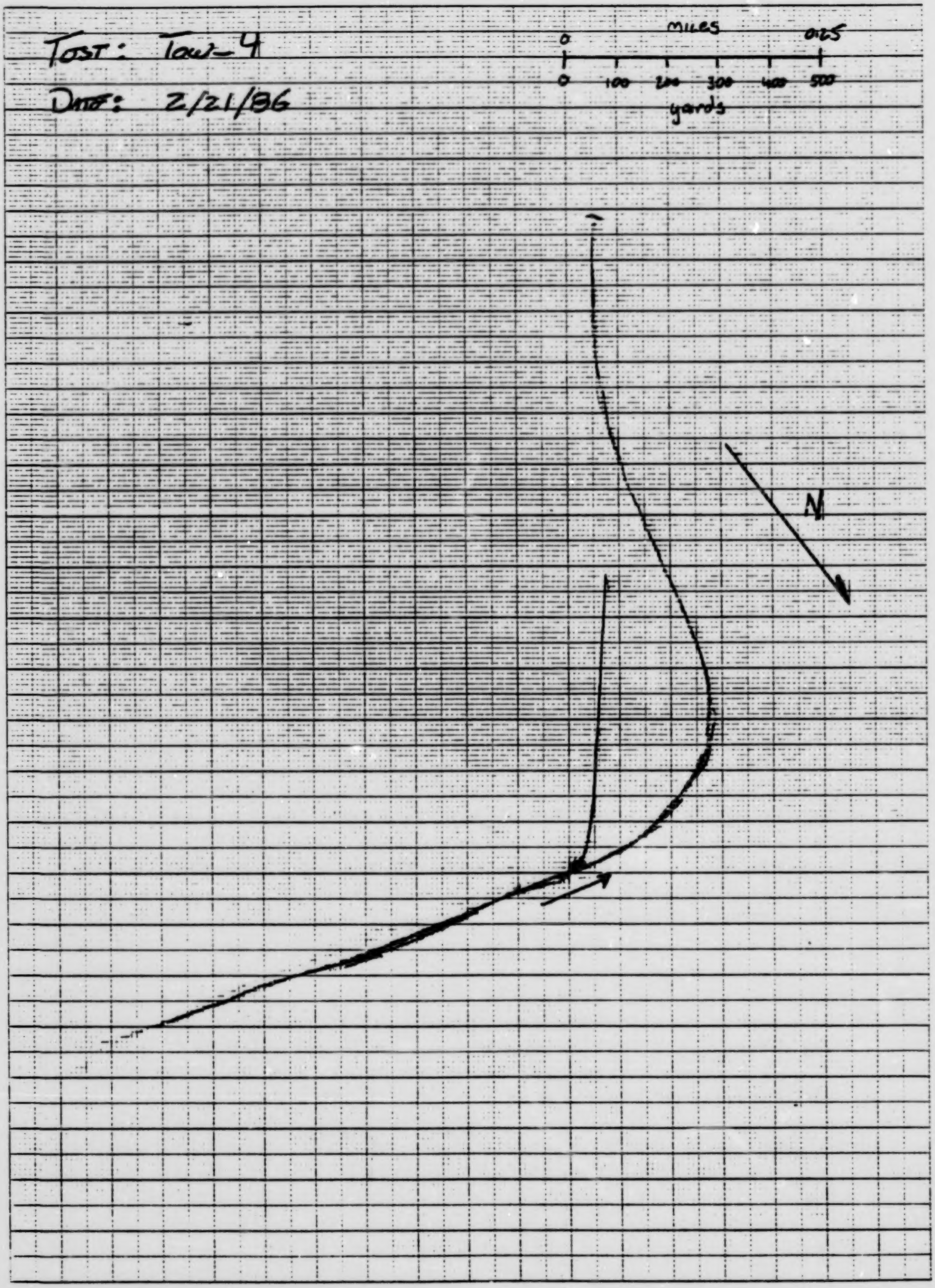
Test: Tour 3

Date: 2/20/86


0
miles
0.25
0
100
200
300
400
500
yards
N

461510

K&E 10 X 10 TO THE CENTIMETER
KEUFFEL & ESSER CO.



Test: Tow-4

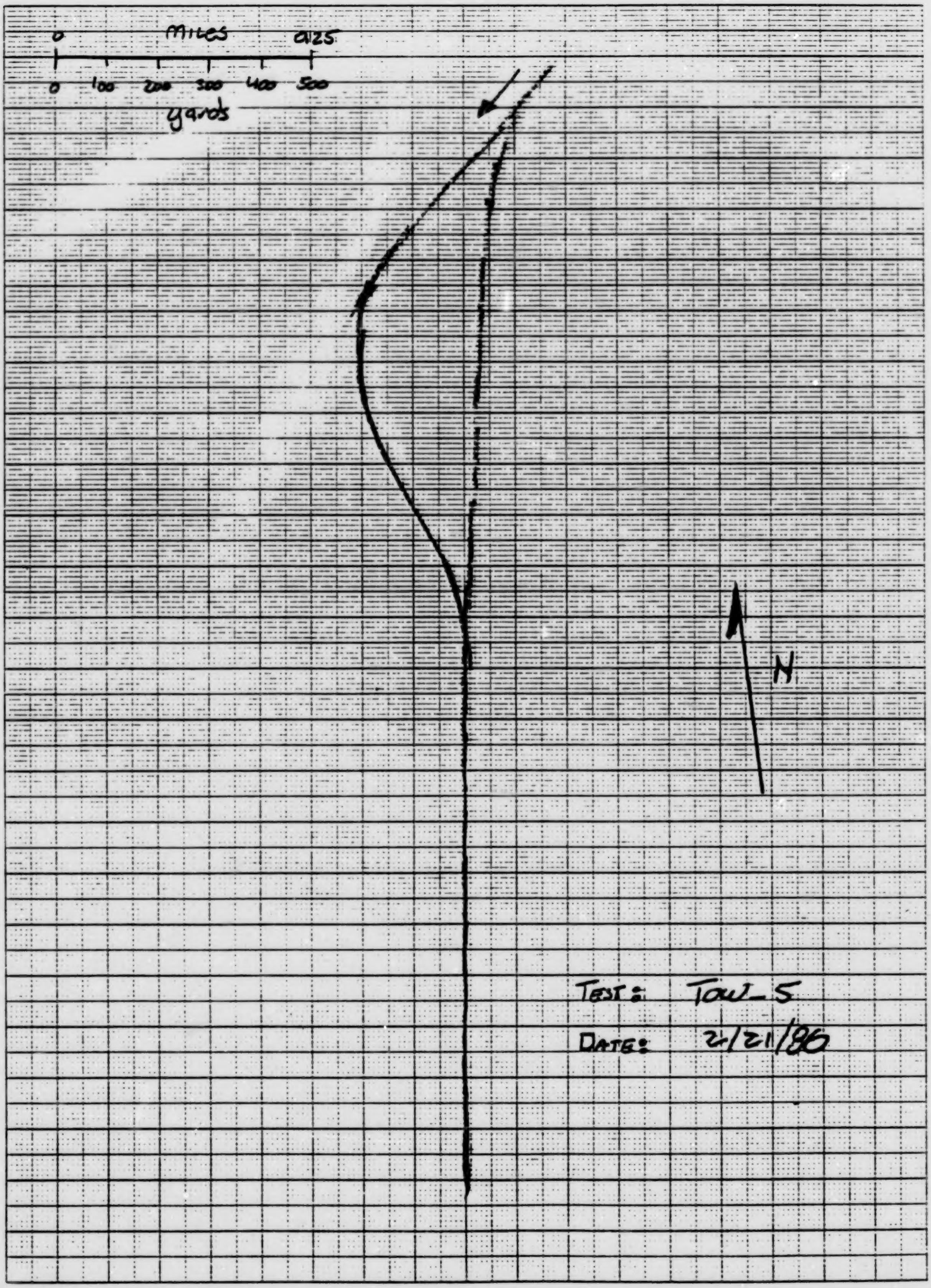
Date: 2/21/86

461510

K&E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

461510

K-E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

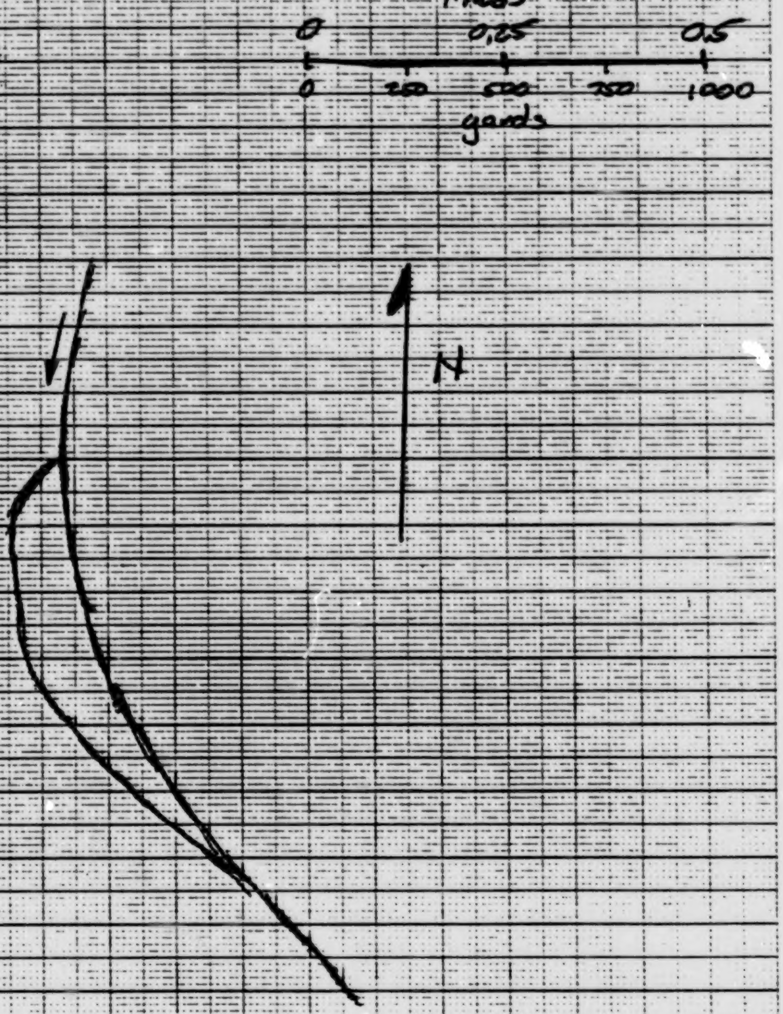

0
Miles
0.25
0
100
200
300
400
500
yards
N

TEST: TOW 5

DATE: 2/21/86

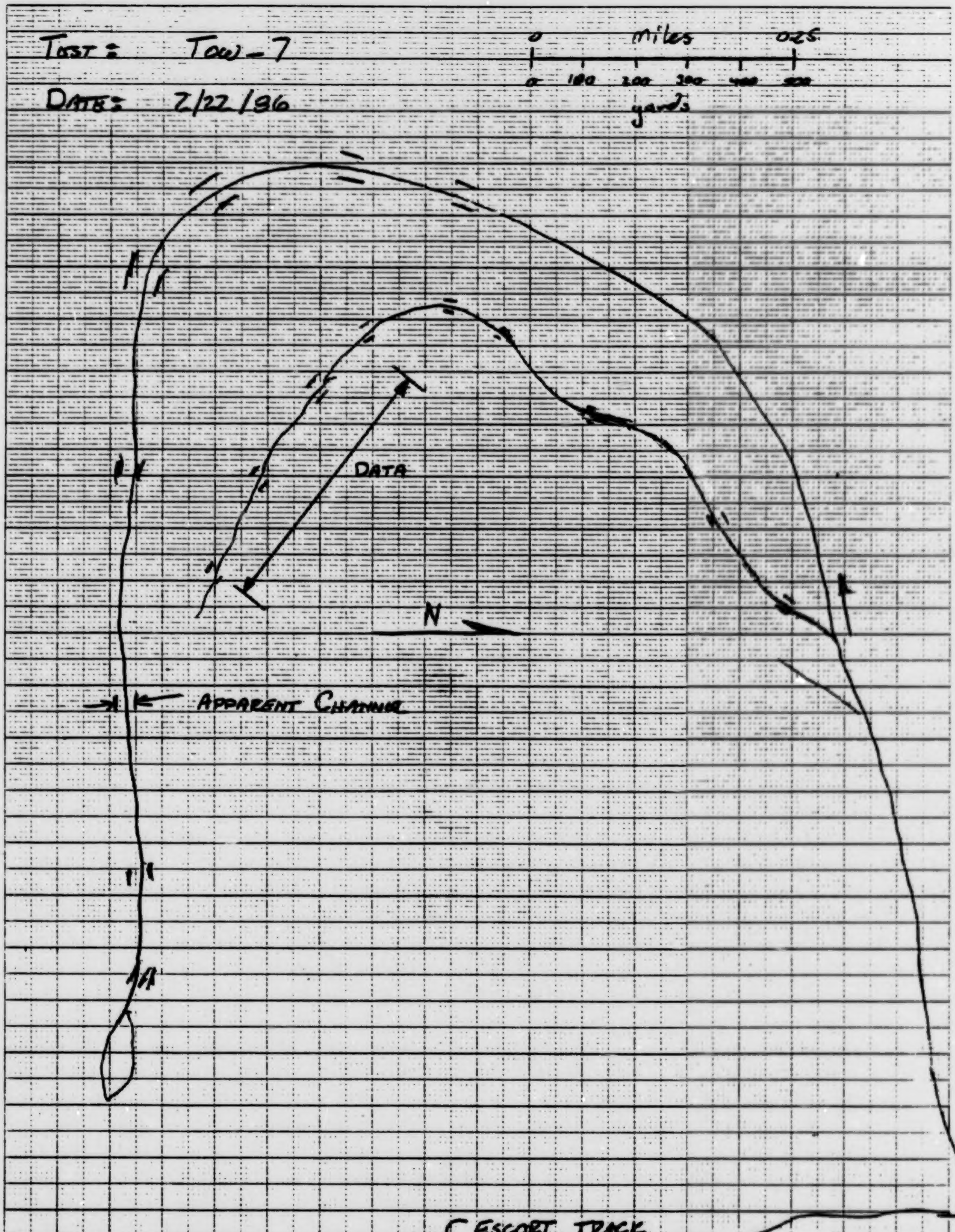
TEST: Tow-6

DATE: 2/21/86


Miles
0
0.25
0.5
0
250
500
750
1000
yards
N

461510

K-E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO MADE IN U.S.A.



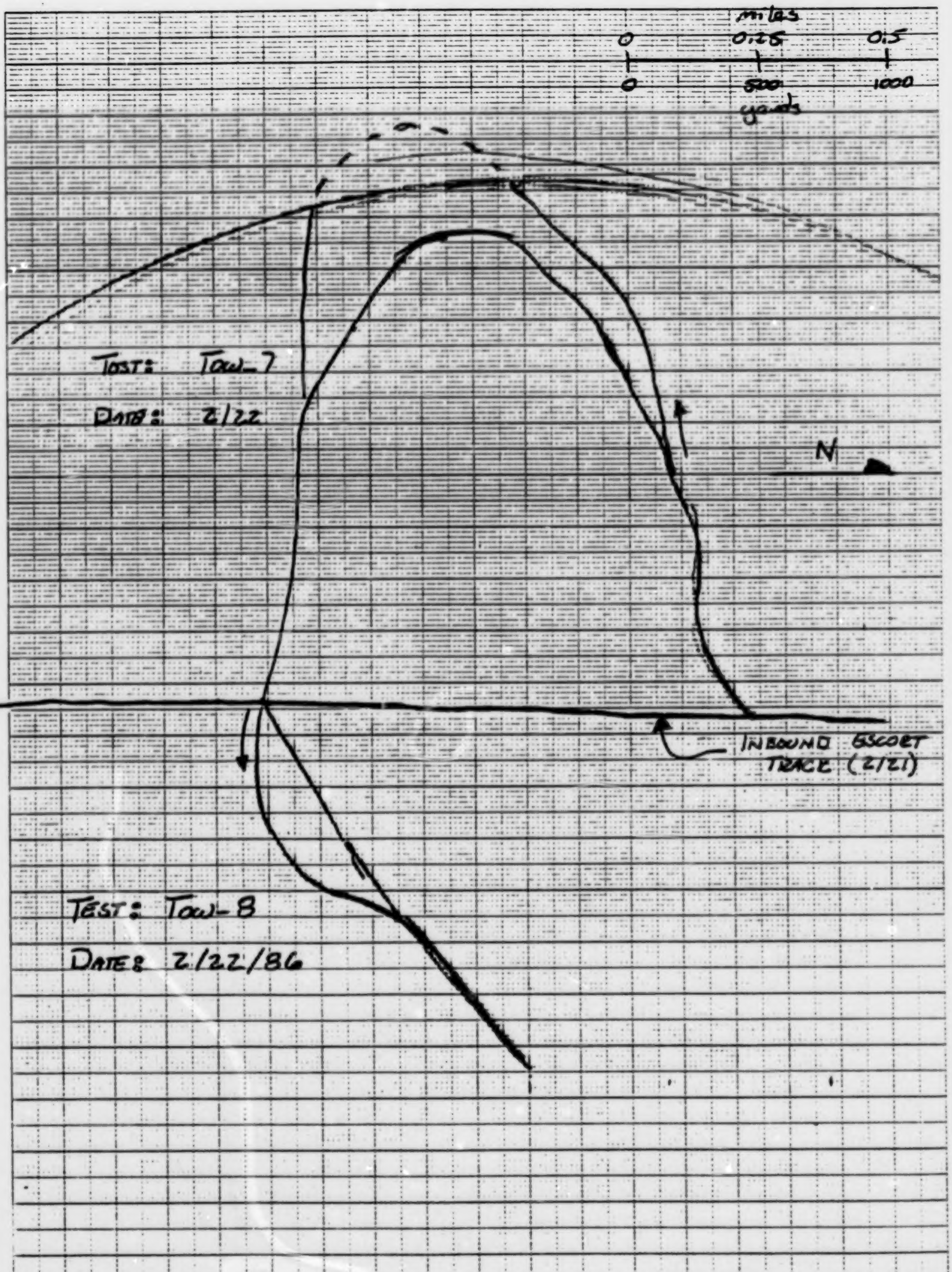
TEST: TOW-7

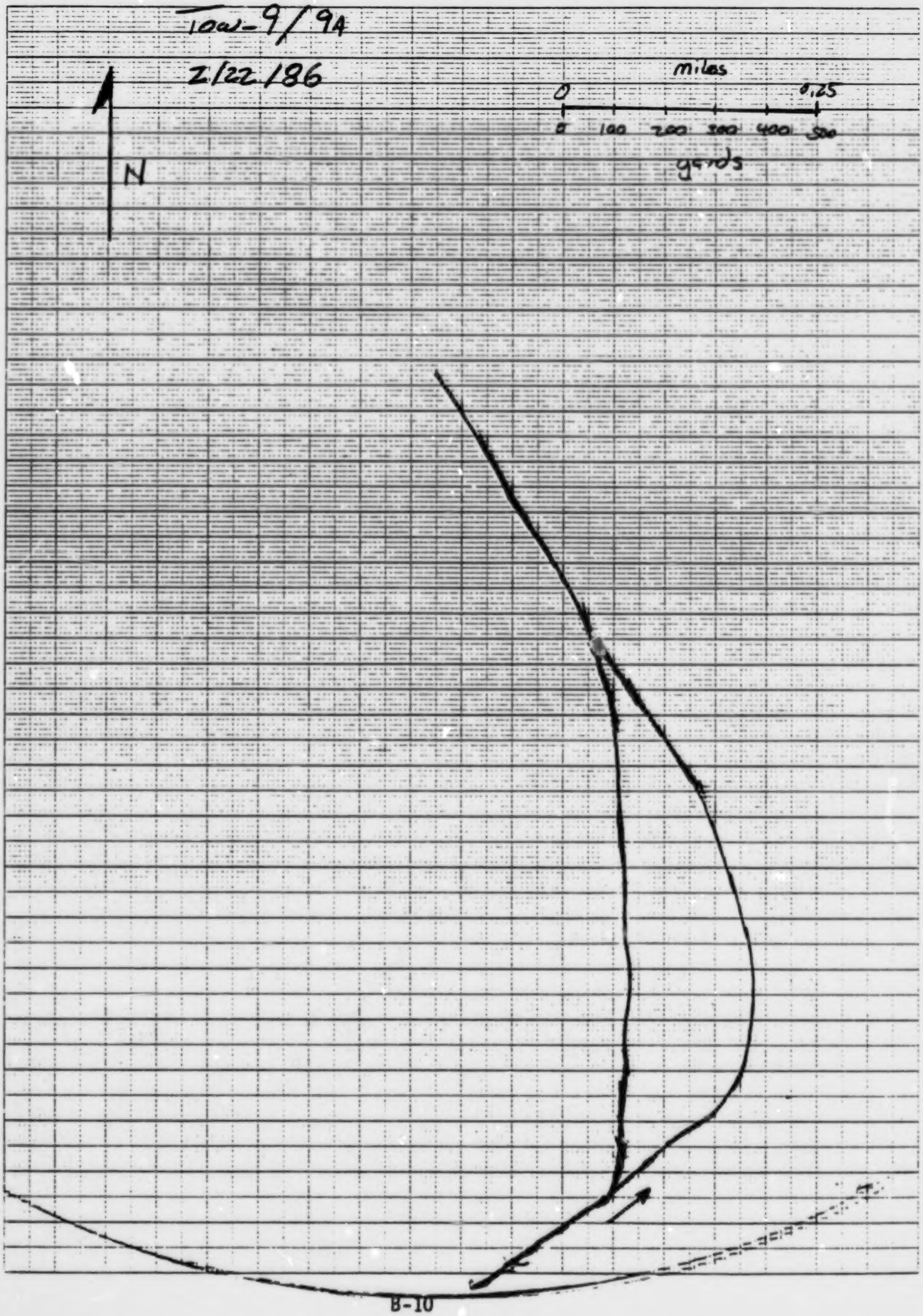
DATE: 2/22/86

K-E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.
461510

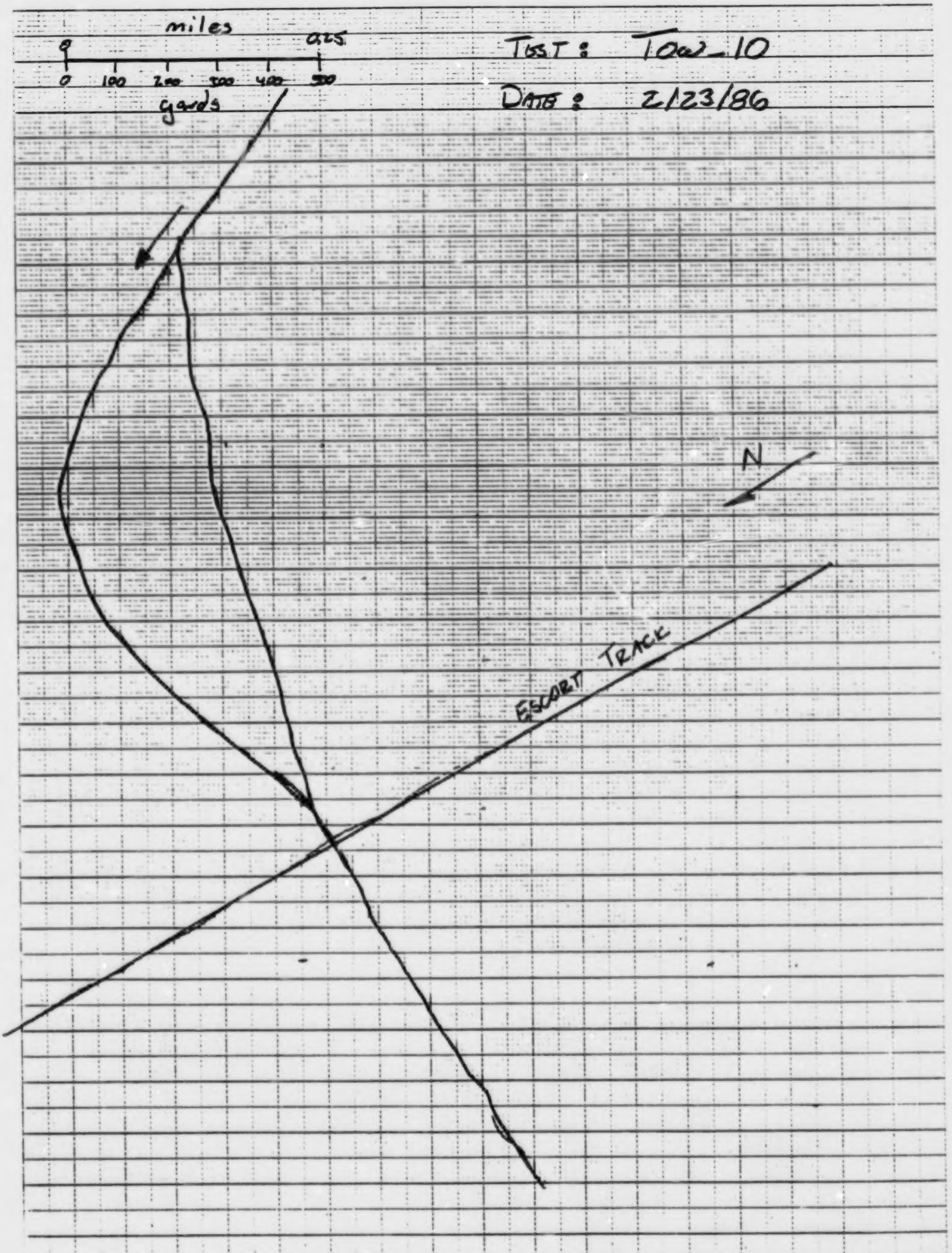
461510

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

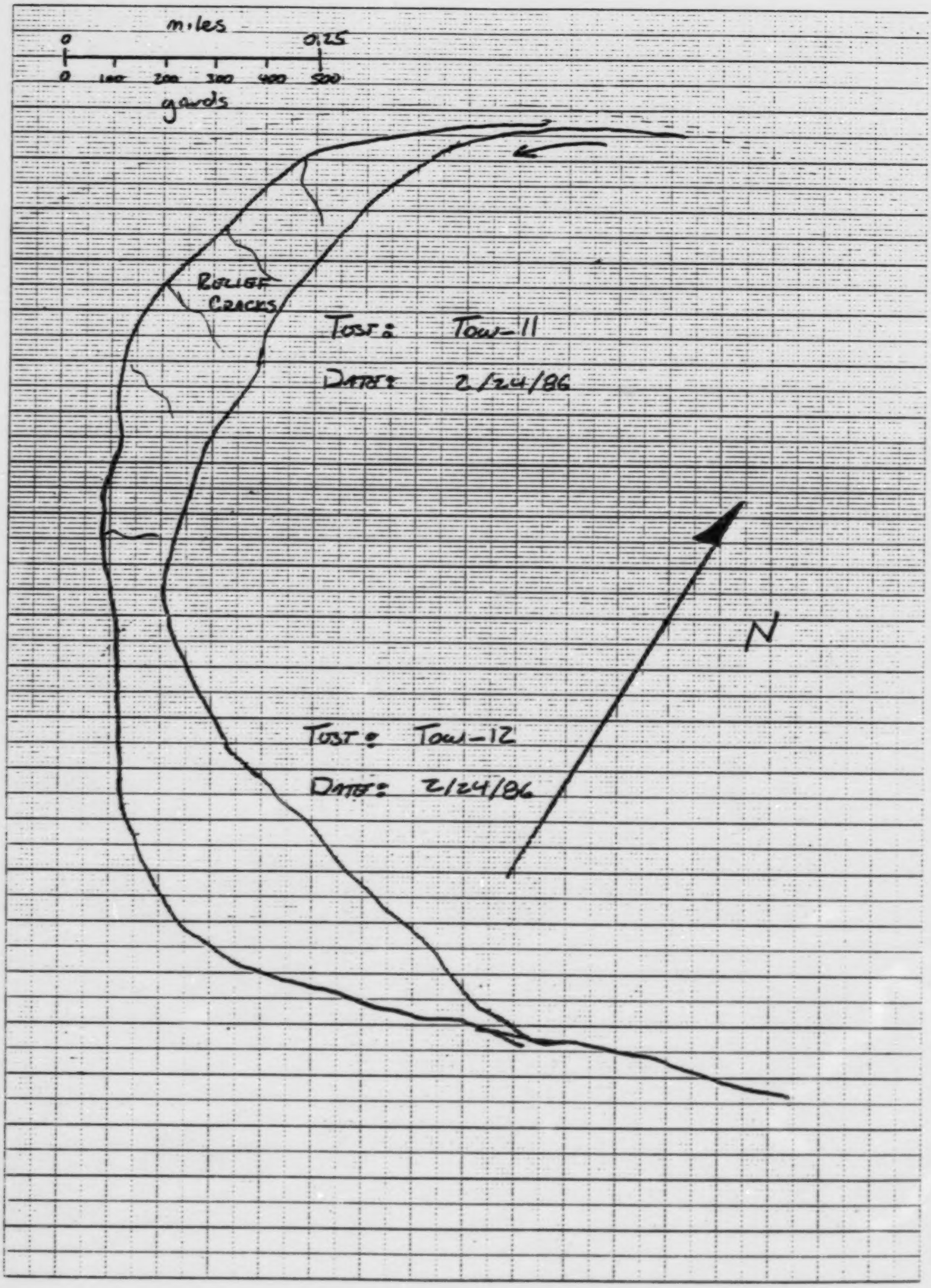

miles
0
0.25
0.5
0
500
1000
yards
TEST: TOW-7
DATE: 2/22
N
INBOUND ESCORT TRACE (2/21)
TEST: TOW-8
DATE: 2/22/86


Tow-9/9A
2/22/86
N
miles
0
0.25
0
100
200
300
400
500
yards

K+E 10 X 10 TO THE CENTIMETER
KEUFFEL & ESSER CO.
461510



46 1510
K-E 10 X 10 TO THE CENTIMETER
KEUFFEL & ESSER CO.


miles
0
0.25
0
100
200
300
400
500
yards
RELIEF CRACKS
N

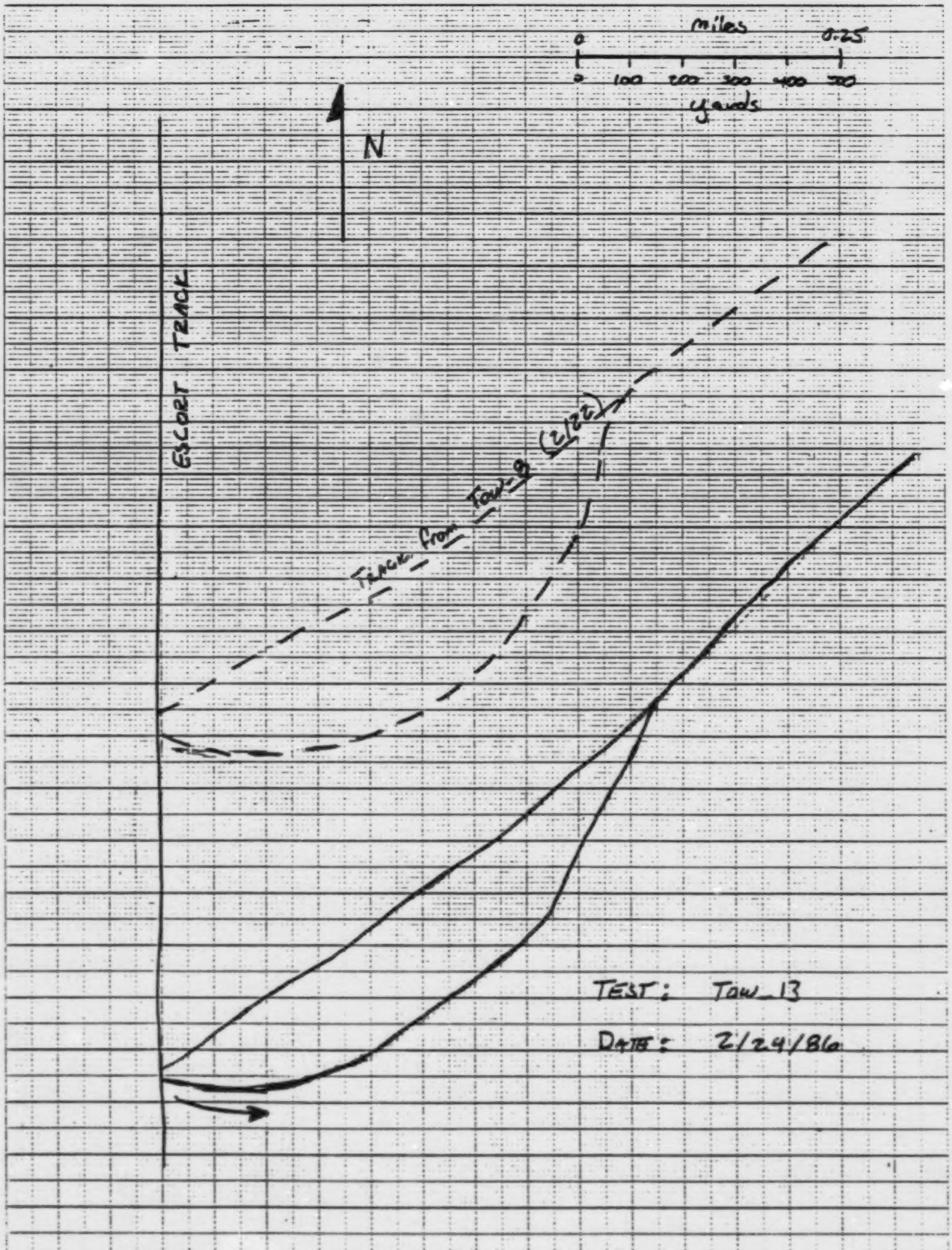
TEST: TOW-11

DATE: 2/24/86

TEST: TOW-12

DATE: 2/24/86

461510
K+E 10 X 10 TO THE CENTIMETER
KEUFFEL & ESSER CO.



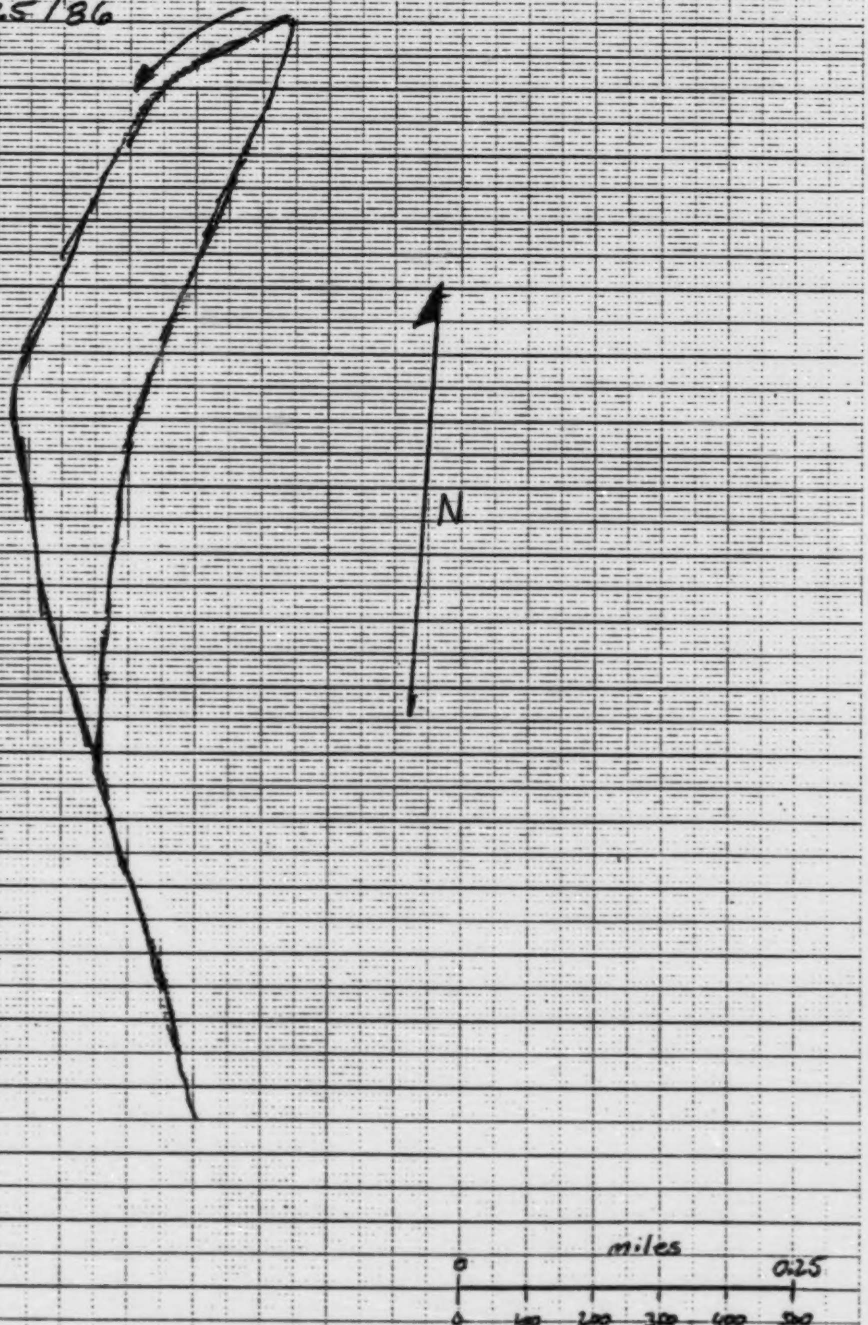
TEST: TOW_13

DATE: 2/24/86

K+E 10 X 10 TO THE CENTIMETER KEUFFEL & ESSER CO. 46 1510

TEST: Tow 14

DATE: 2/25/86

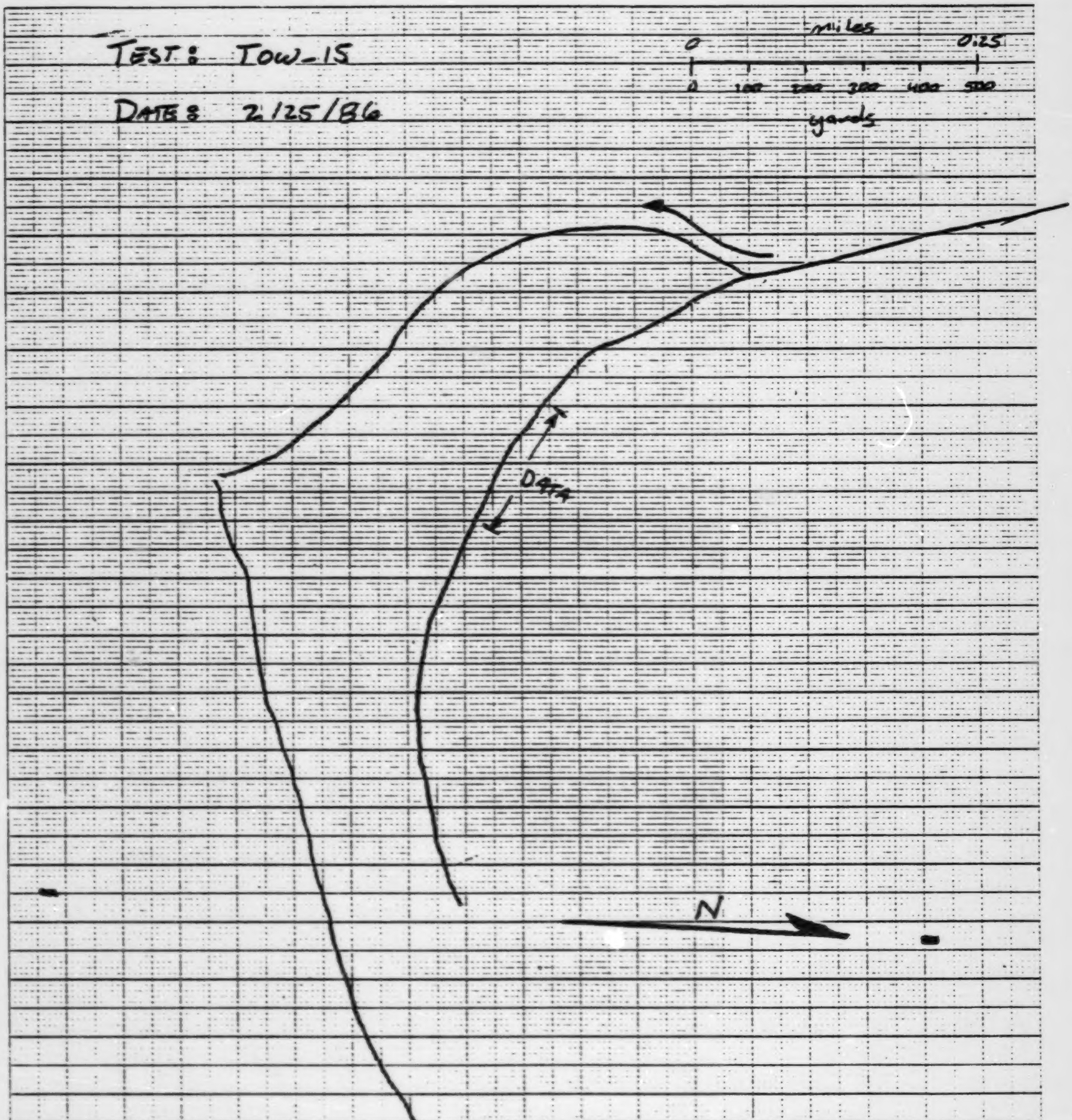

N
miles
0
0.25
0
100
200
300
400
500
yards

461510

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

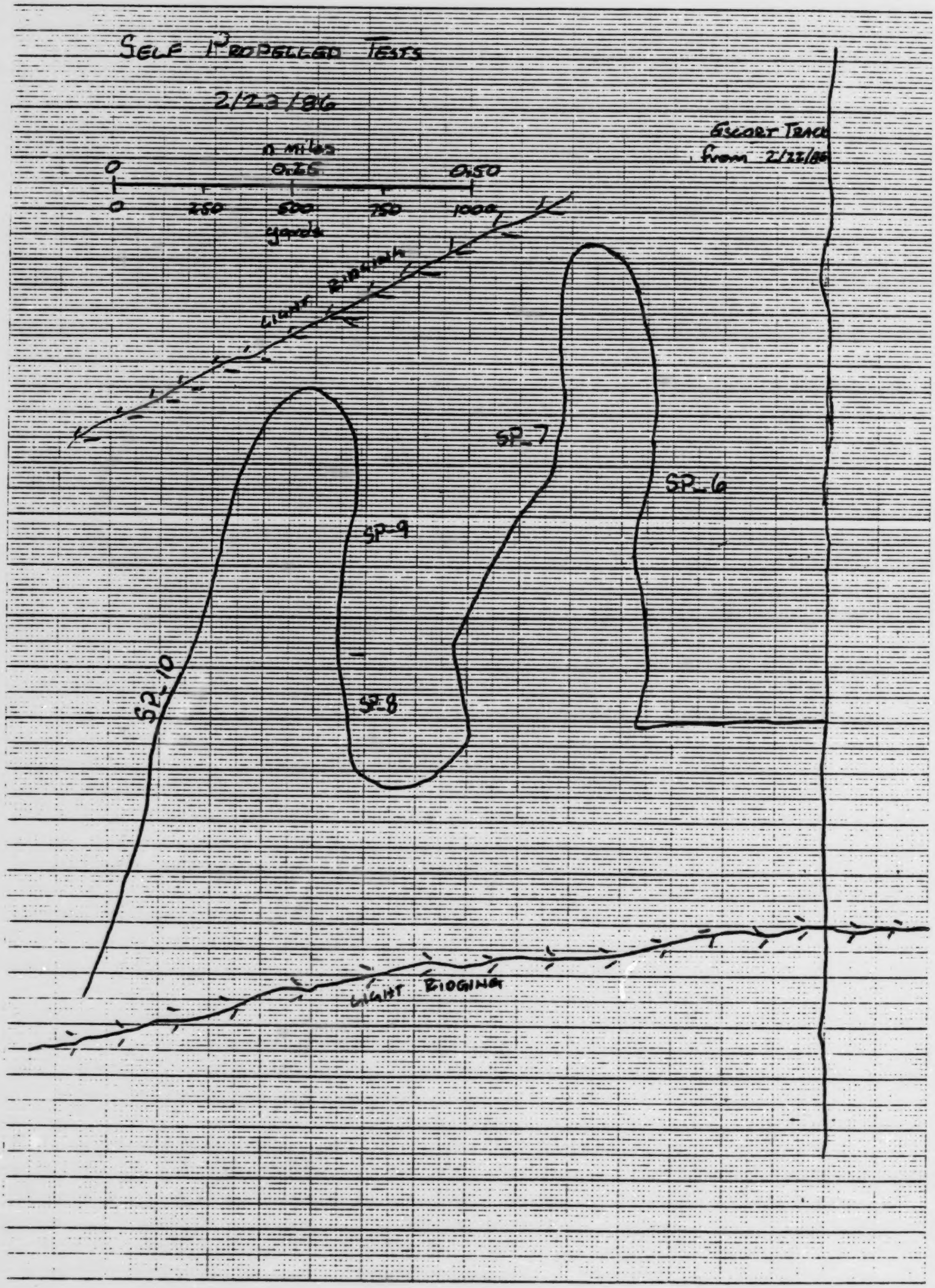
TEST: TOW-15

DATE: 2/25/86


miles
0
0.25
0
100
200
300
400
500
yards
DATA
N

461510

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

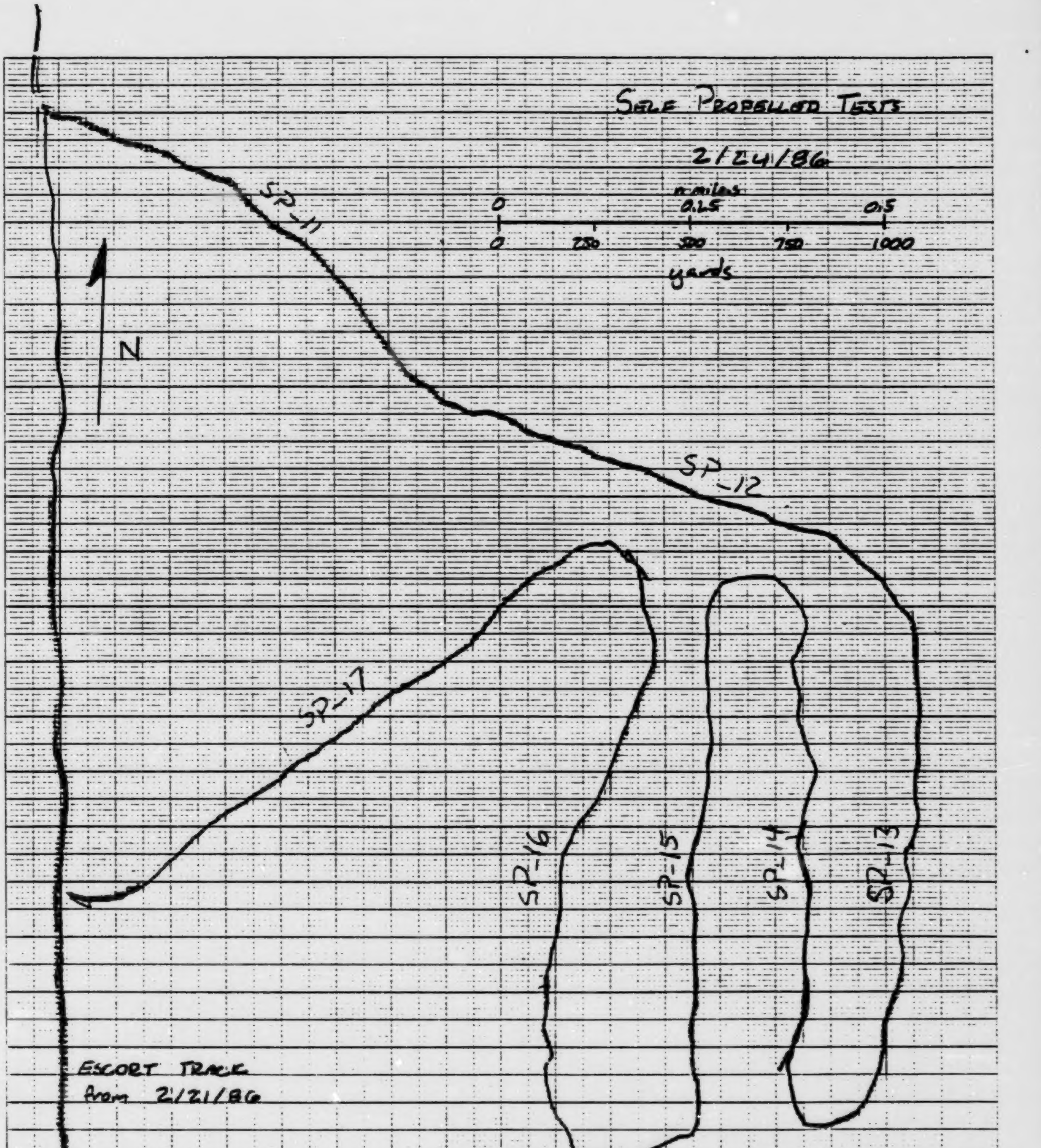

SELF PROPELLED TESTS
2/23/86
n miles
0
0.25
0.50
0
250
500
750
1000
yards
ESCORT TRACK
from 2/22/8
LIGHT RIDGING
SP-7
SP-6
SP-9
SP-8
SP-10
LIGHT RIDGING

46 1523

K&E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO.

461510

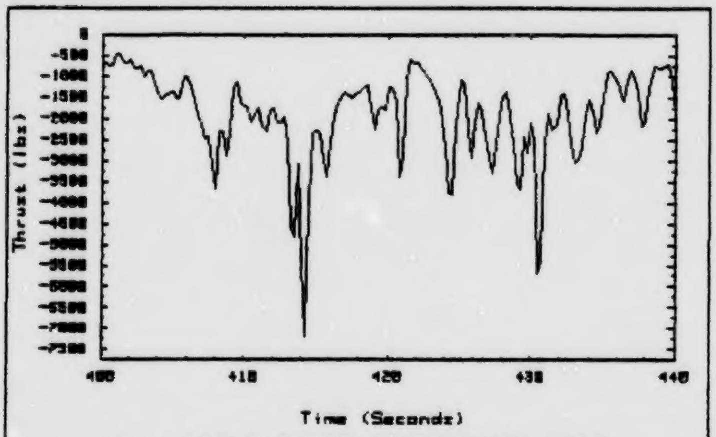
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO.


SELF PROPELLED TESTS
2/24/86
n miles
0
0.25
0.5
0
250
500
750
1000
yards
N
SP-11
SP-12
SP-13
SP-14
SP-15
SP-16
SP-17
ESCORT TRACK
from 2/21/86
MINNEAPOLIS
SHOAL LIGHT

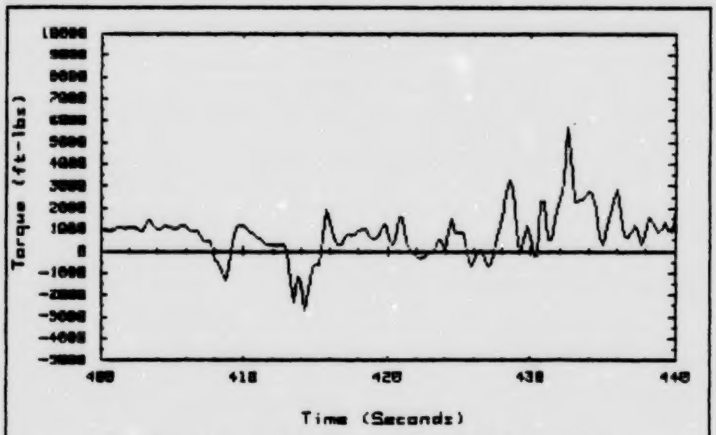
APPENDIX C

TOWED TEST RESULTS

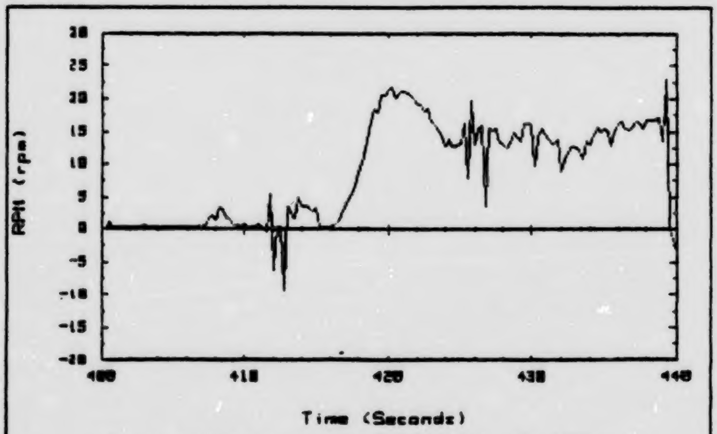
```
Test Results for Test TOW_1:  02/19/86, 13:16:12
              For the Interval Between  400  sec and  440  sec

   CHANNEL                              MAXIMUM      MINIMUM       MEAN       STDRD DEV

 1  Thrust (lbs)                         -464.1      -7189.5     -1908.8        1072.2
 2  Torque (ft-lbs)                      5688.7      -2699.4       792.9        1093.4
 3  RPM (rpm)                              22.9         -9.5         8.6           7.7
 4  Ship Speed (kts)                        4.7          2.9         4.0            .3
 5  Tow-Line Tension (lbs)              37385.2      17537.4     26326.1        4642.4
 6  Net Resistance (lbs)                35185.2      13994.8     24417.2        4514.9

              Test Results for Test TOW_1:  02/19/86, 13:16:12
              For the Interval Between  400  sec and  440  sec

             Average Ship Speed                     4.0   kts
             Average Thrust                     -1908.8   lbs
             Average Torque                       792.9   ft-lbs
             Average RPM                            8.6   RPM
             Average Tow-Line Tension           26326.1   lbs
             Average Net Resistance             24417.2   lbs
```



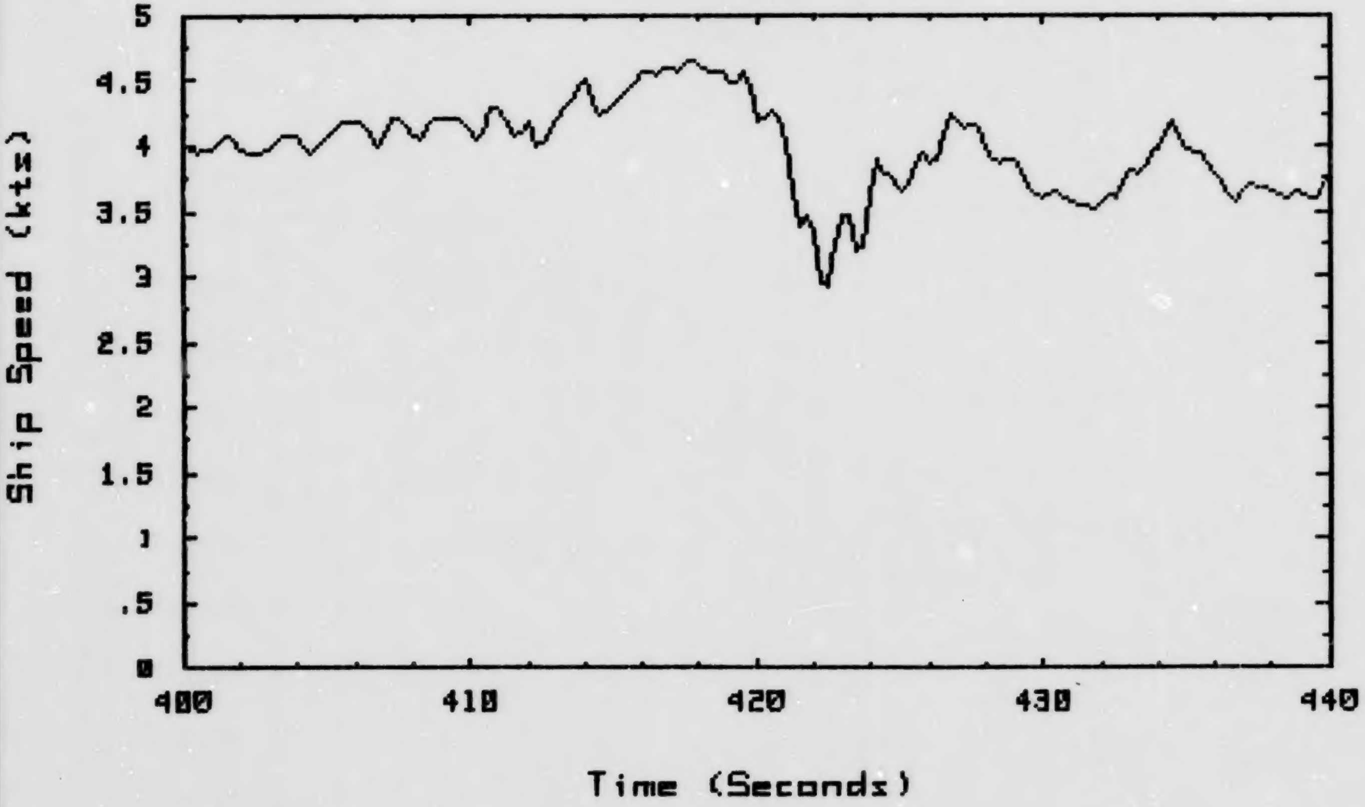
FULL-SCALE TOWED RESISTANCE TEST
TOW 1



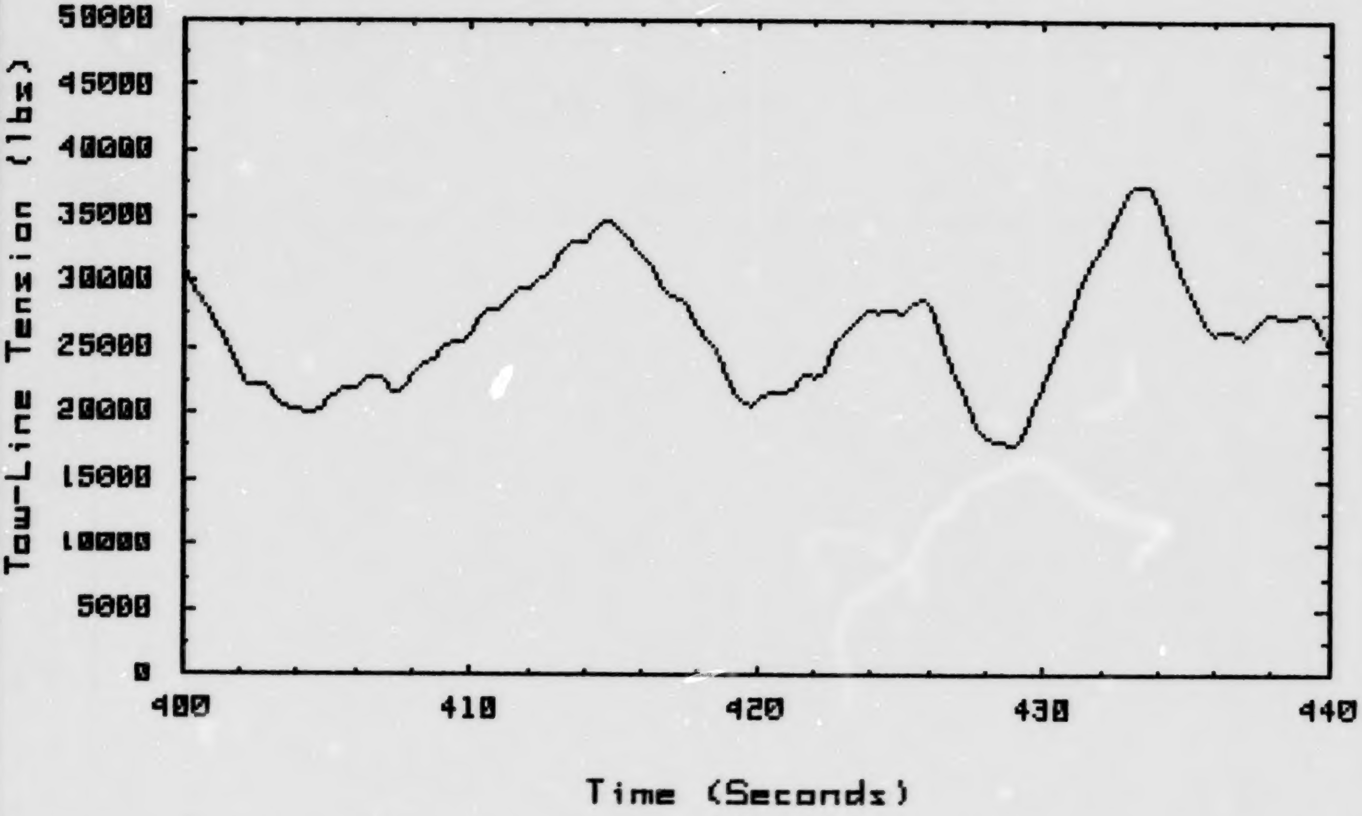
FULL-SCALE TOWED RESISTANCE TEST
TOW 1



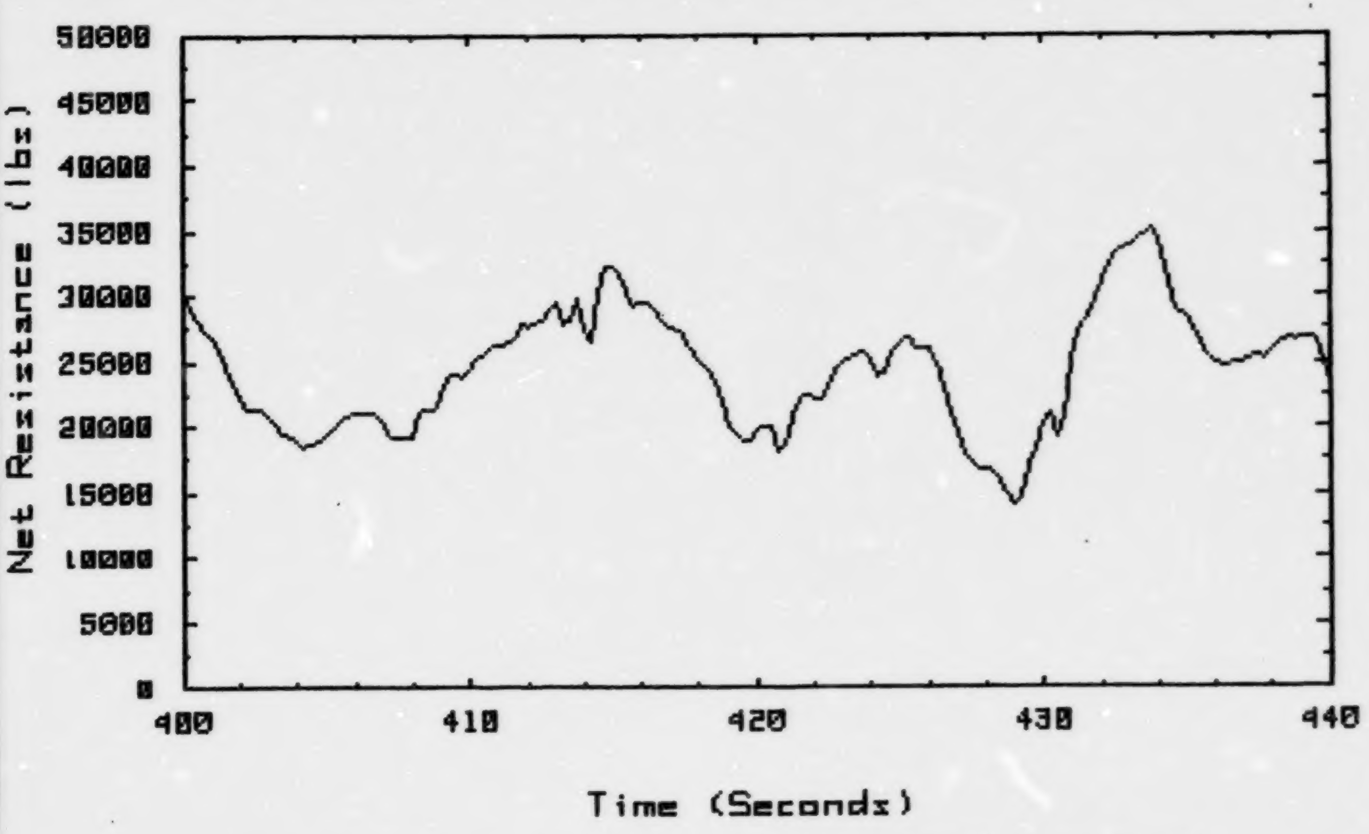
FULL-SCALE TOWED RESISTANCE TEST
TOW 1



FULL-SCALE TOWED RESISTANCE TEST
TOW 1

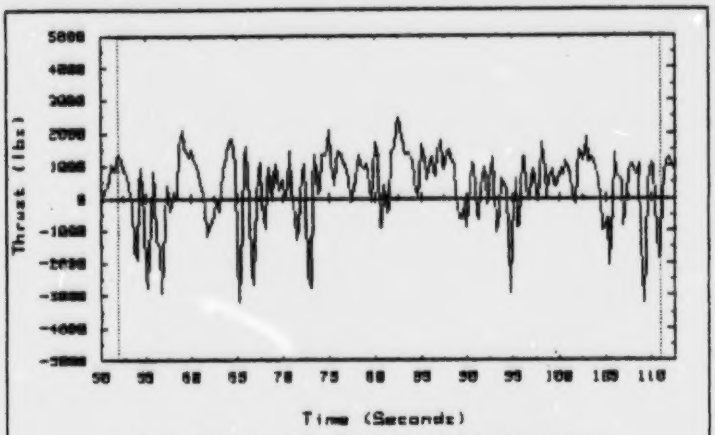


FULL-SCALE TOWED RESISTANCE TEST
TOW 1

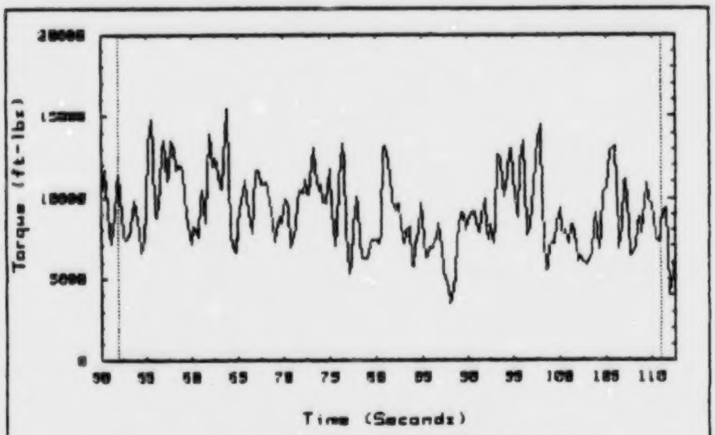


FULL-SCALE TOWED RESISTANCE TEST
TOW 1

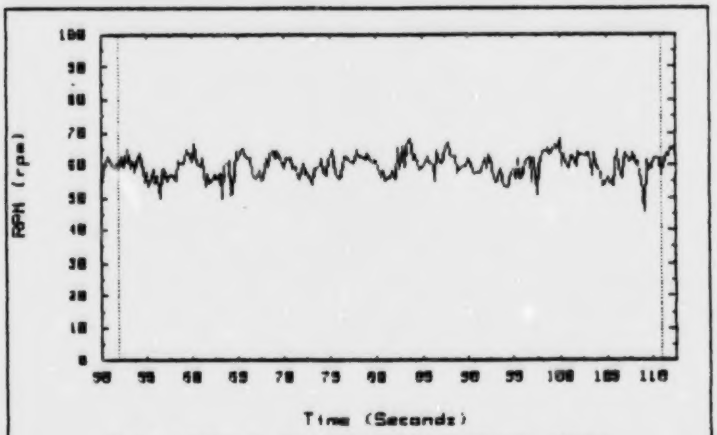
```
Test Results for Test TOW_2:  02/20/86, 11:01:44
            For the Interval Between  52  sec and  111  sec

  CHANNEL                               MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                         2456.5     -3179.6      337.2        1105.5
 2  Torque (ft-lbs)                     15499.4      3531.6     9201.0        2276.9
 3  RPM (rpm)                              68.0        45.3       59.9           3.7
 4  Ship Speed (kts)                        6.7         3.3        5.0            .3
 5  Tow-Line Tension (lbs)              47533.1     22854.7    36767.1        6173.5
 6  Net Resistance (lbs)                47971.7     22395.3    37104.3        6307.3

            Test Results for Test TOW_2:  02/20/86, 11:01:44
            For the Interval Between  52  sec and  111  sec

           Average Ship Speed                      5.0   kts
           Average Thrust                        337.2   lbs
           Average Torque                       9201.0   ft-lbs
           Average RPM                            59.9   RPM
           Average Tow-Line Tension            36767.1   lbs
           Average Net Resistance              37104.3   lbs
```



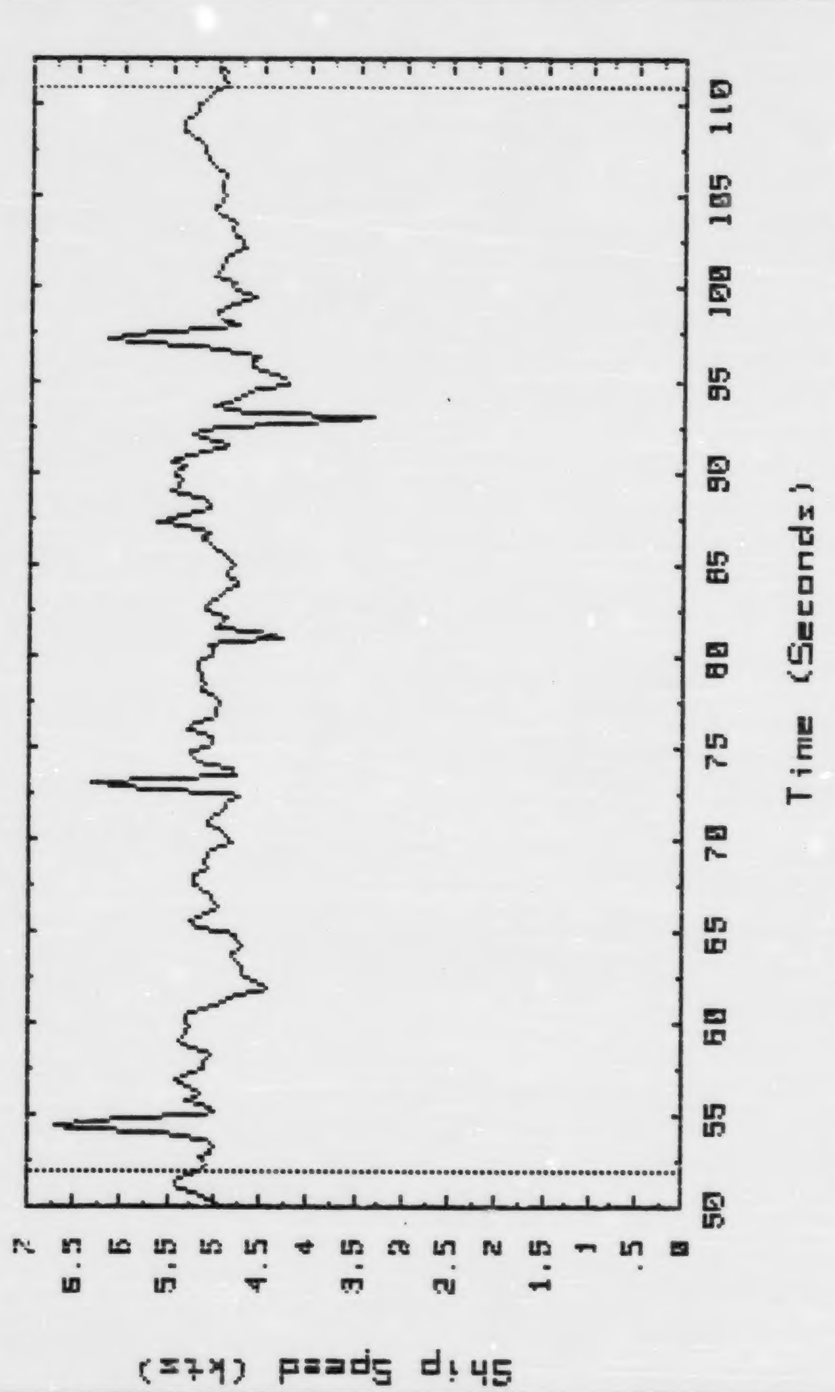
FULL-SCALE TOWED RESISTANCE TEST
TOW 2



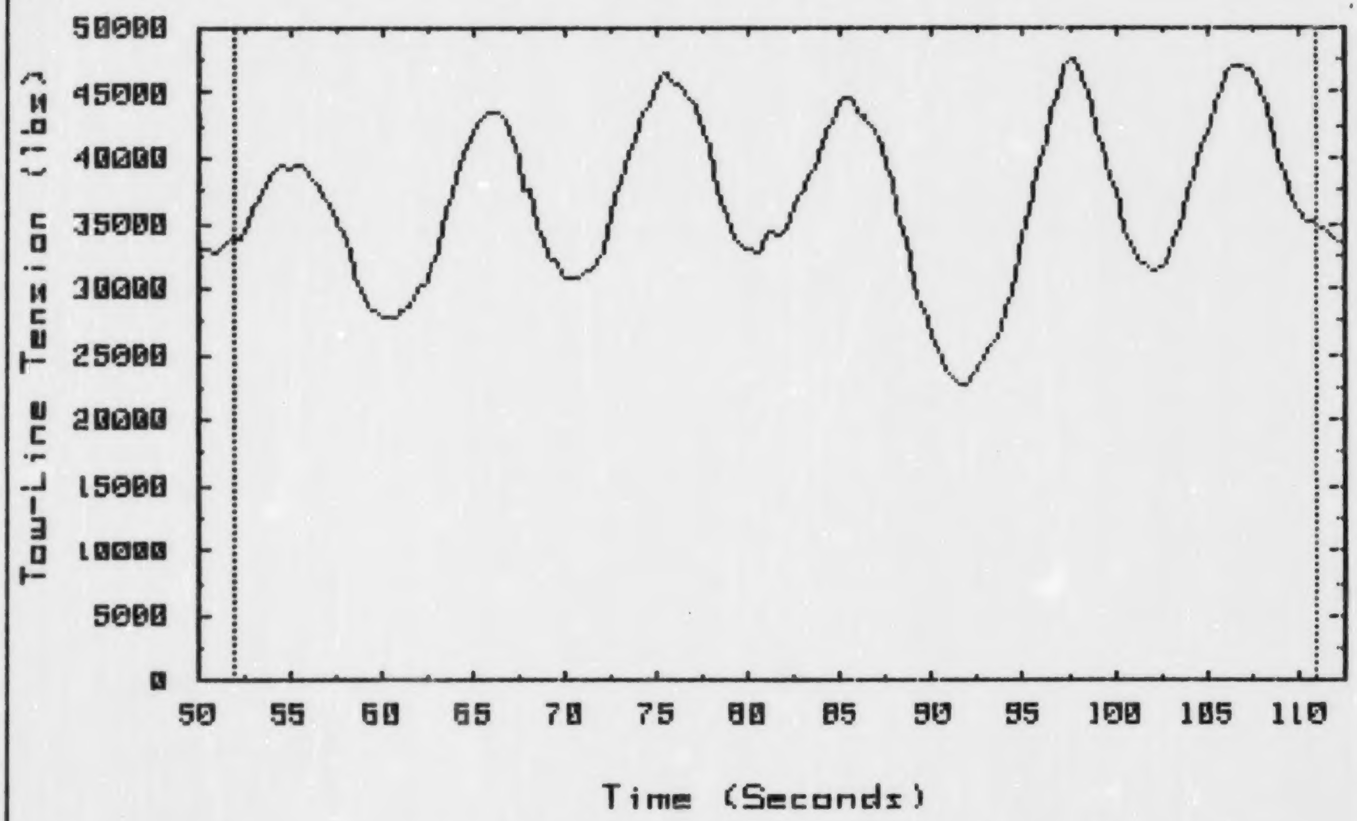
FULL-SCALE TOWED RESISTANCE TEST
TOW 2



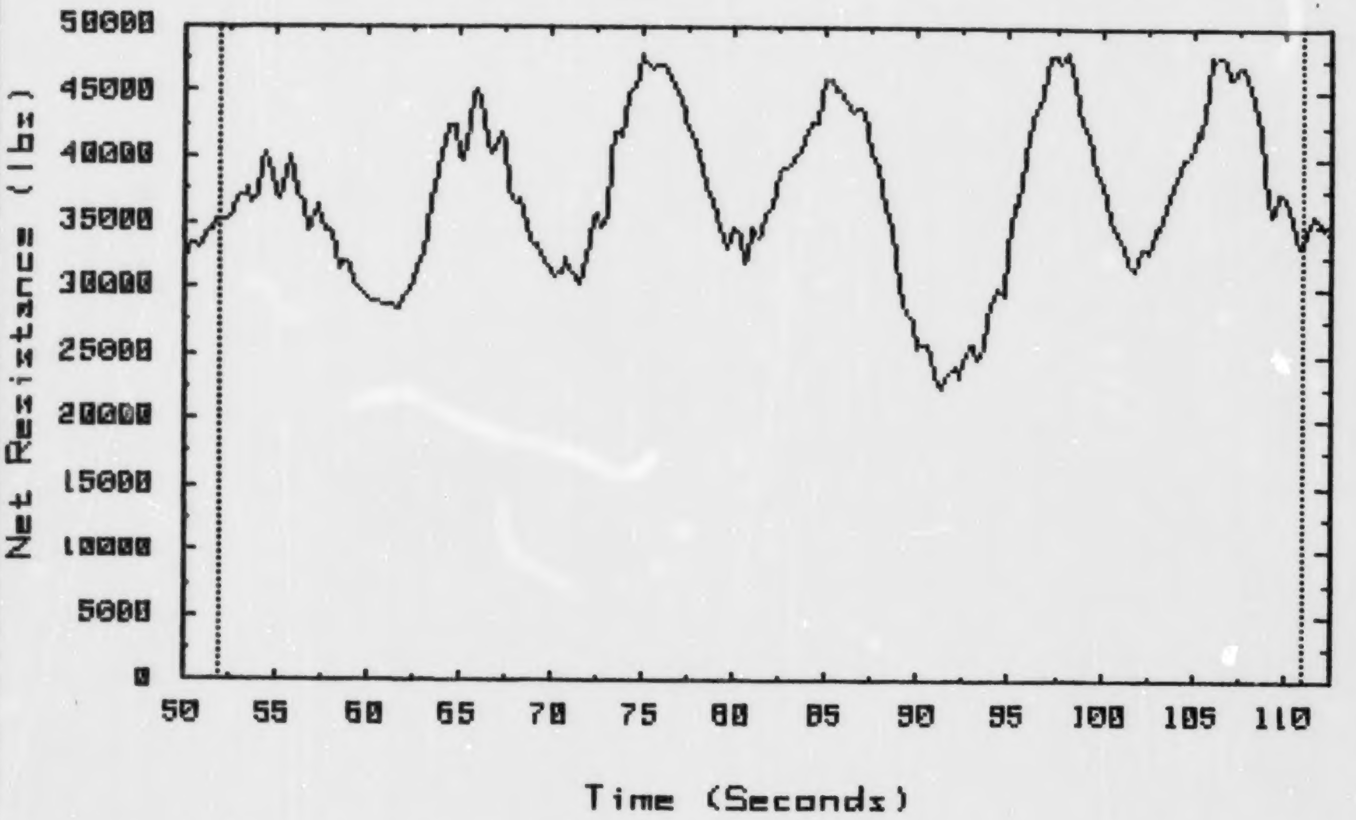
FULL-SCALE TOWED RESISTANCE TEST
TOW 2



FULL-SCALE TOWED RESISTANCE TEST
TOW 2

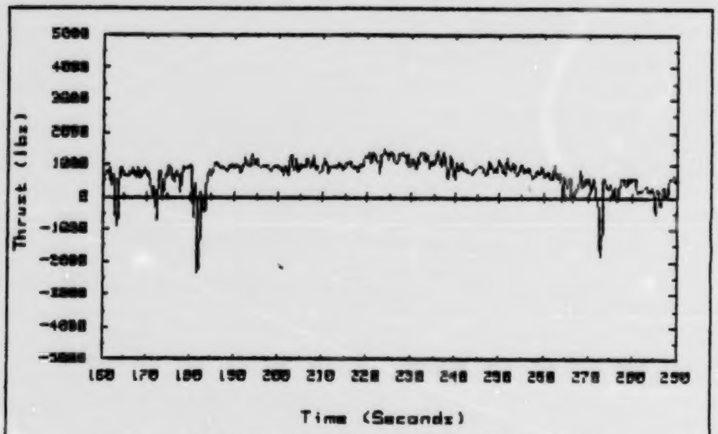


FULL-SCALE TOWED RESISTANCE TEST
TOW 2

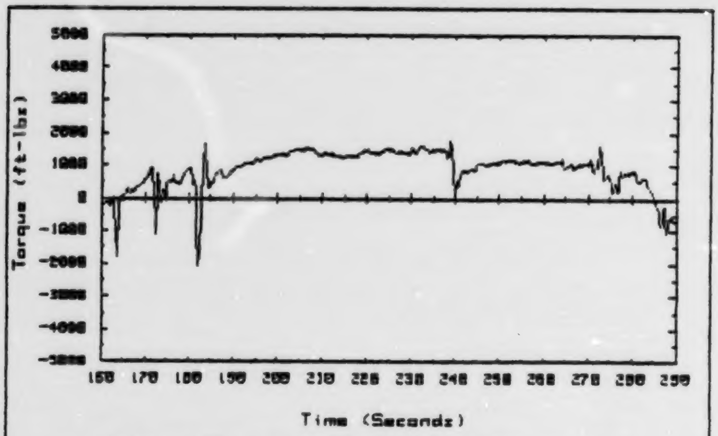


FULL-SCALE TOWED RESISTANCE TEST
TOW 2

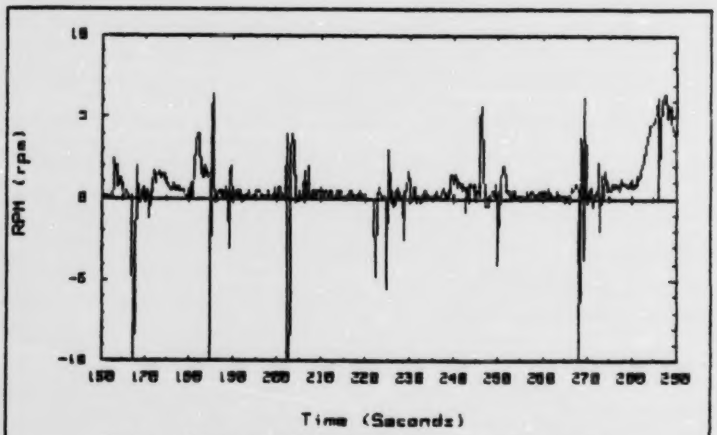
```
                 Average Net Resistance

   Test Results for Test TOW_3:  02/20/86, 19:28:05
                 For the Interval Between  160  sec and  290  sec

      CHANNEL                             MAXIMUM     MINIMUM        MEAN      STDRD DEV

   1  Thrust (lbs)                         1499.2     -2337.1       733.3          456.7
   2  Torque (ft-lbs)                      1753.9     -2066.2       874.6          610.2
   3  RPM (rpm)                               6.5       -16.2          .6            2.0
   4  Ship Speed (kts)                        3.7         1.4         2.5             .5
   5  Tow-Line Tension (lbs)              38774.6     20712.1     31169.2         4105.3
   6  Net Resistance (lbs)                39563.4     21595.6     31902.5         4041.1

                 Test Results for Test TOW_3:  02/20/86, 19:28:05
                 For the Interval Between  160  sec and  290  sec

                Average Ship Speed                   2.5   kts
                Average Thrust                     733.3   lbs
                Average Torque                     874.6   ft-lbs
                Average RPM                           .6   RPM
                Average Tow-Line Tension         31169.2   lbs
                Average Net Resistance           31902.5   lbs
```



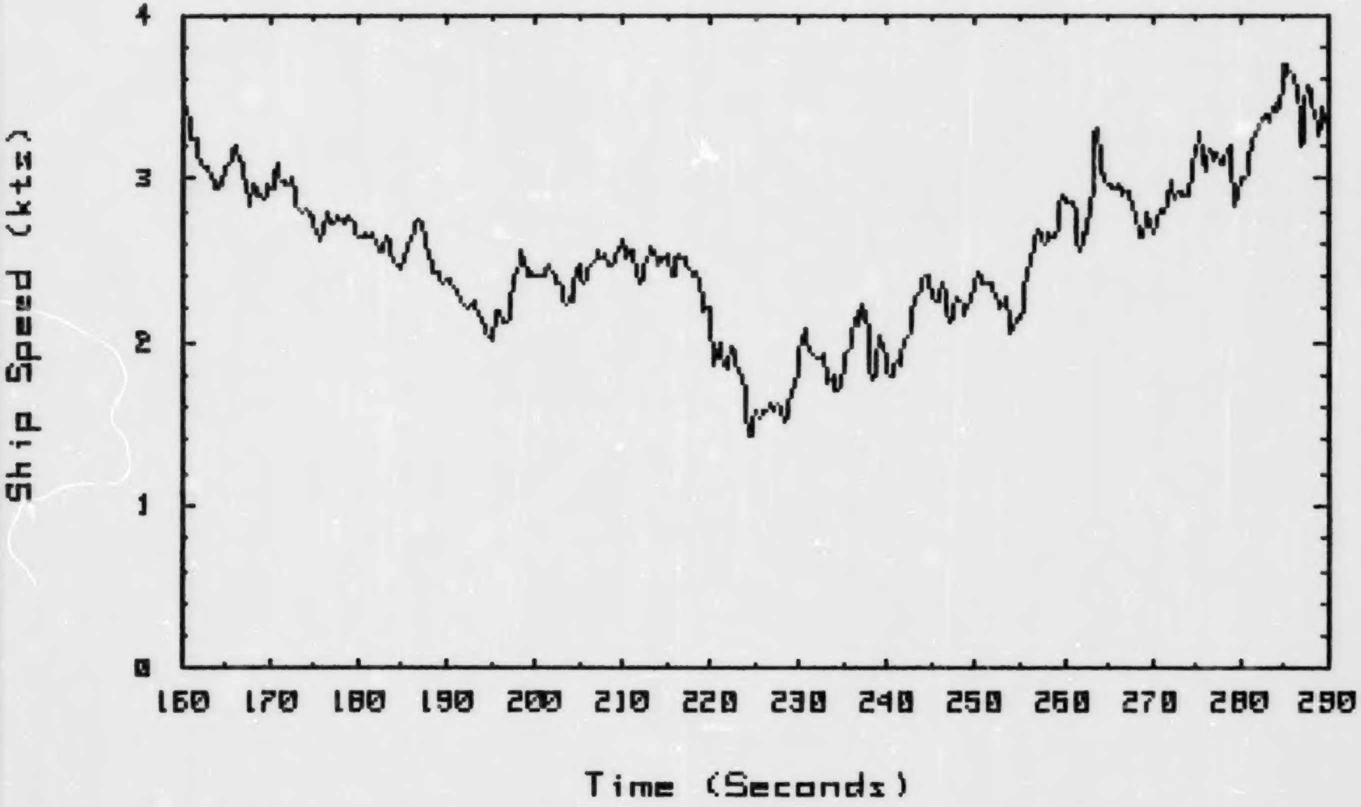
FULL-SCALE TOWED RESISTANCE TEST
TOW 3



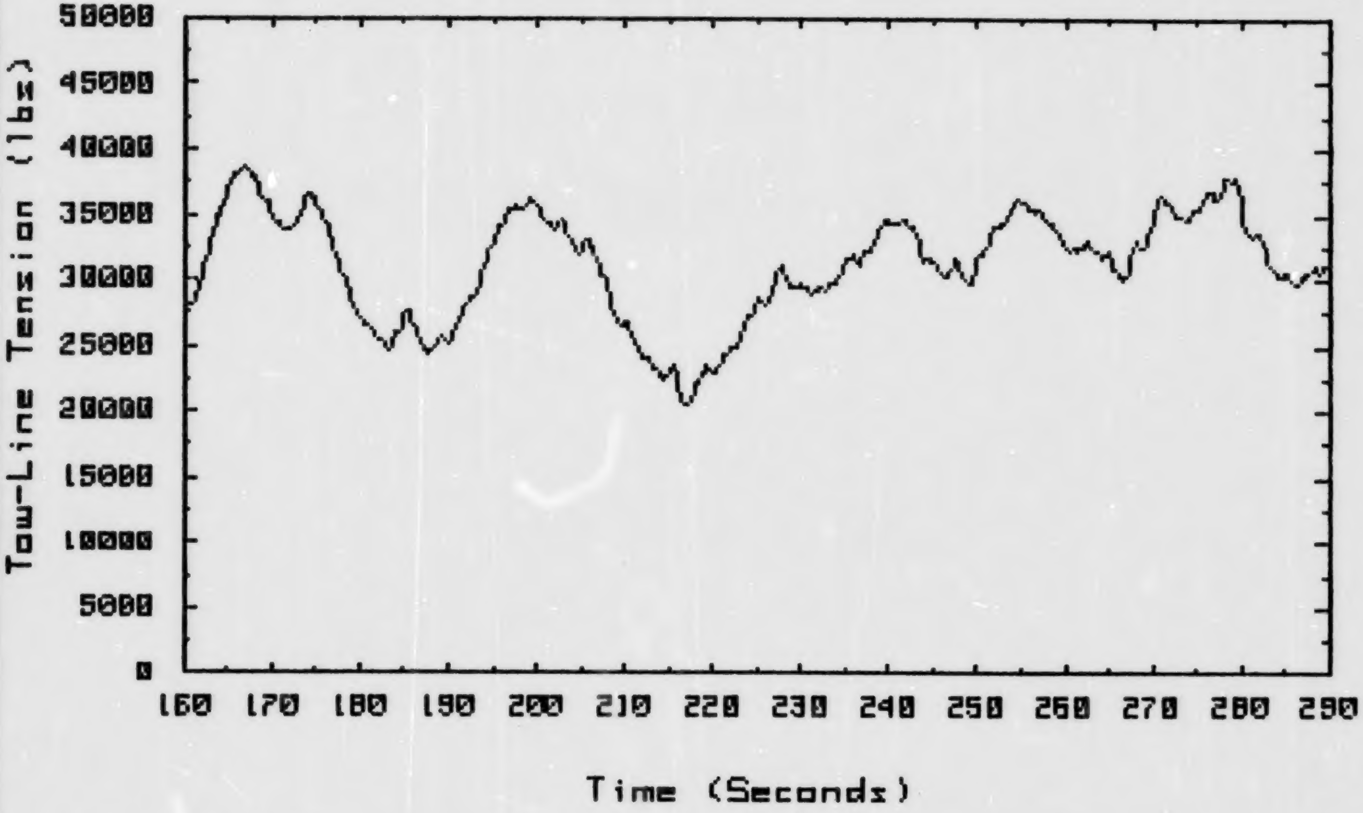
FULL-SCALE TOWED RESISTANCE TEST
TOW 3



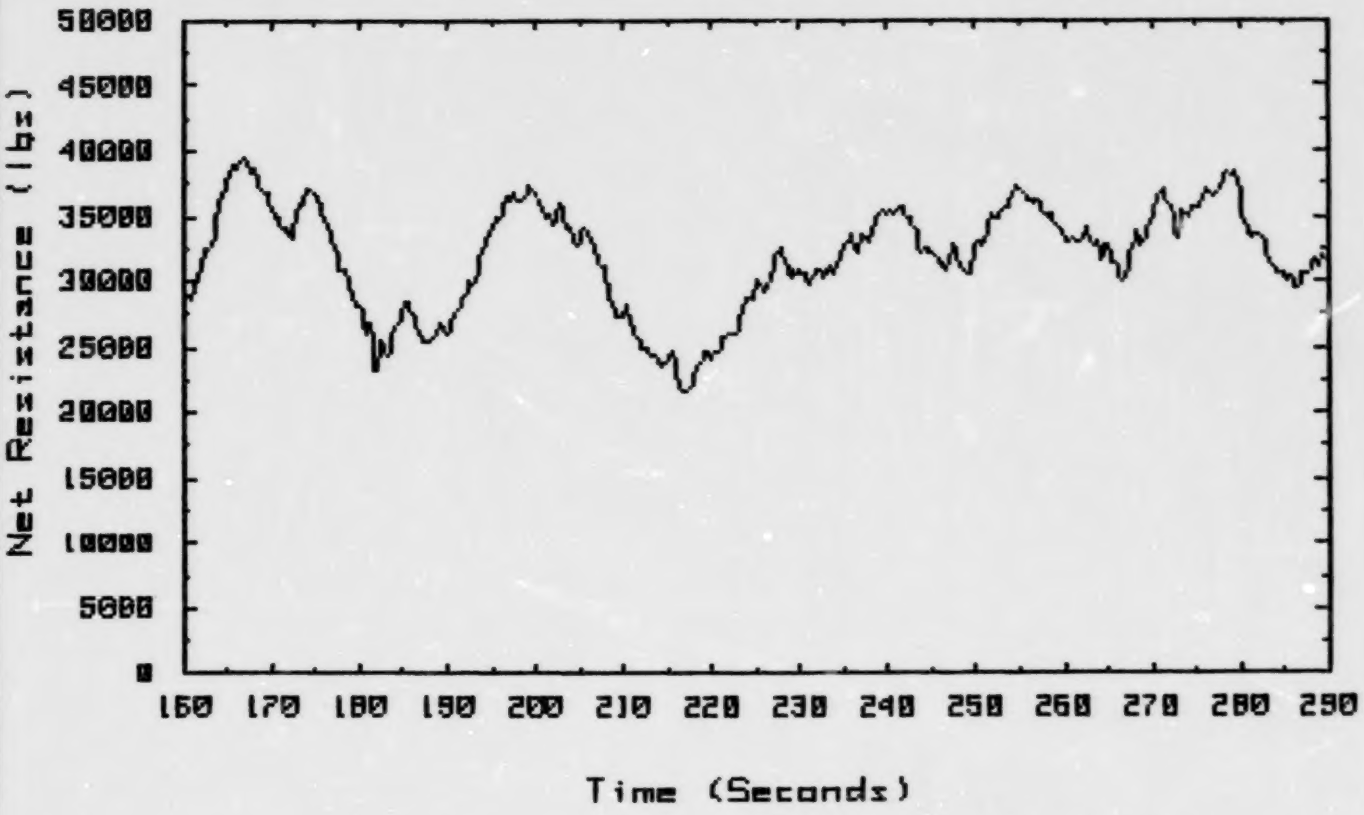
FULL-SCALE TOWED RESISTANCE TEST
TOW 3



FULL-SCALE TOWED RESISTANCE TEST
TOW 3

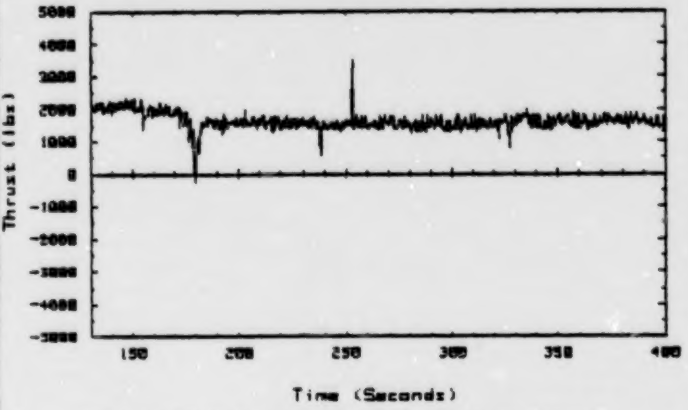


FULL-SCALE TOWED RESISTANCE TEST
TOW 3

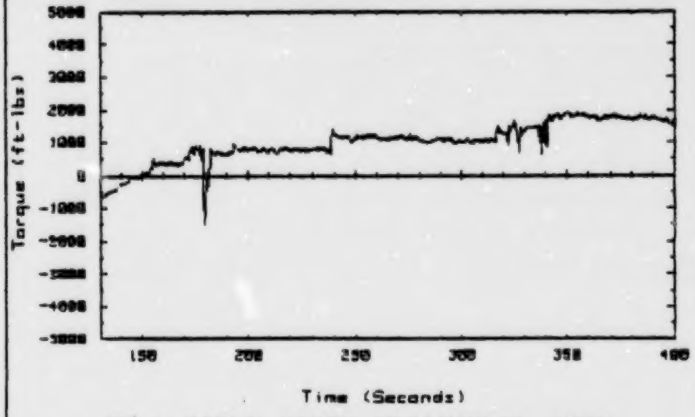


FULL-SCALE TOWED RESISTANCE TEST
TOW 3

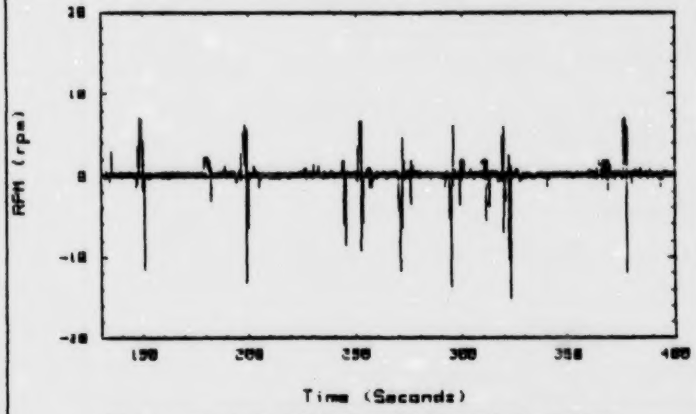
```
Test Results for Test TOW_4:  02/21/86, 12:47:07
              For the Interval Between  130  sec and  400  sec

  CHANNEL                              MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                        3493.4      -248.2      1623.9        260.4
 2  Torque (ft-lbs)                     1895.8     -1496.9       992.4        586.2
 3  RPM (rpm)                              7.0       -15.2          .2          1.7
 4  Ship Speed (kts)                       2.4         -.1         1.8           .5
 5  Tow-Line Tension (lbs)             33090.5     12927.7     21397.1       4072.6
 6  Net Resistance (lbs)               34689.4     14536.8     23021.1       4031.7

              Test Results for Test TOW_4:  02/21/86, 12:47:07
              For the Interval Between  130  sec and  400  sec

             Average Ship Speed                    1.8   kts
             Average Thrust                     1623.9   lbs
             Average Torque                      992.4   ft-lbs
             Average RPM                            .2   RPM
             Average Tow-Line Tension          21397.1   lbs
             Average Net Resistance            23021.1   lbs
```



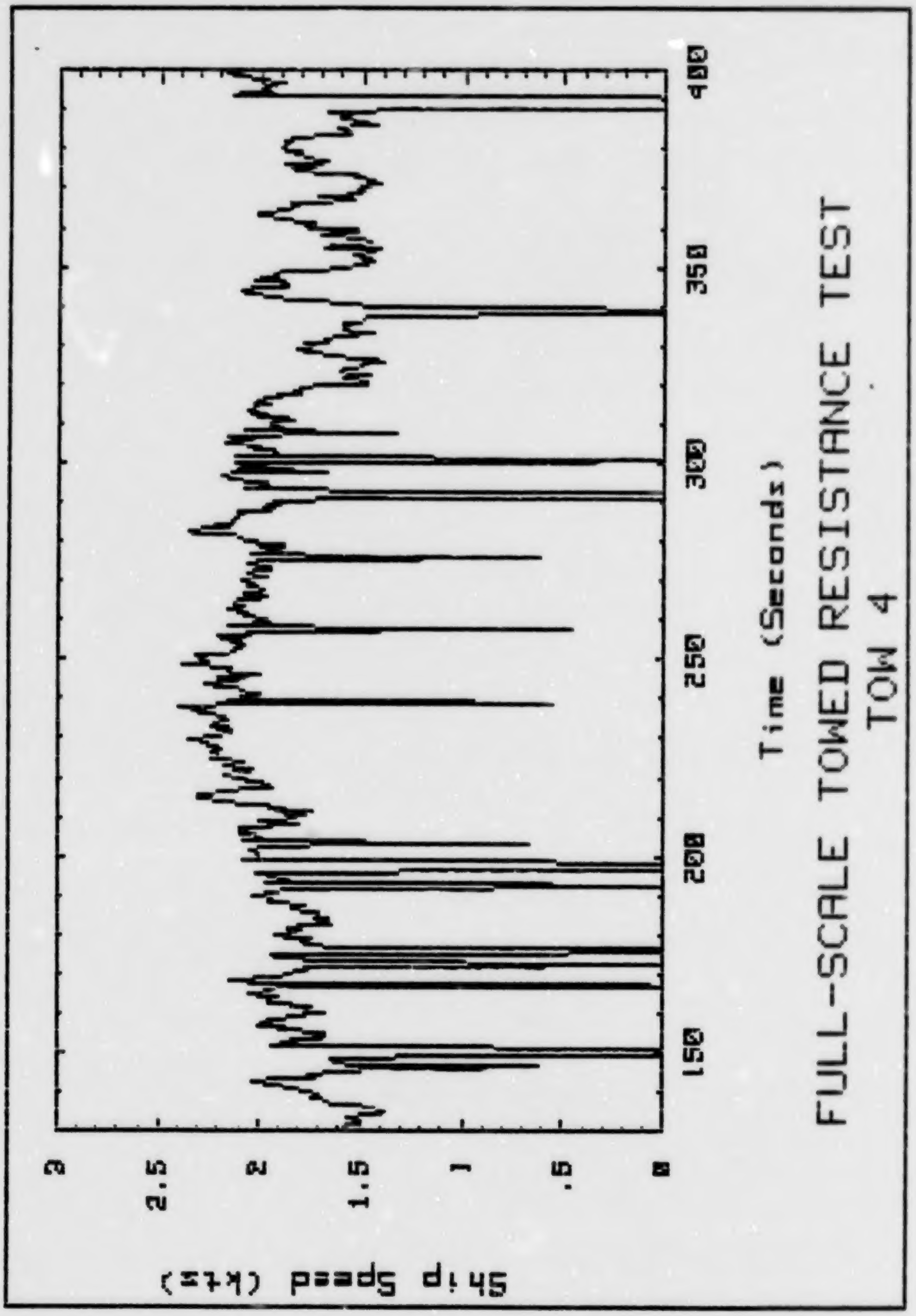
FULL-SCALE TOWED RESISTANCE TEST
TOW 4



FULL-SCALE TOWED RESISTANCE TEST
TOW 4

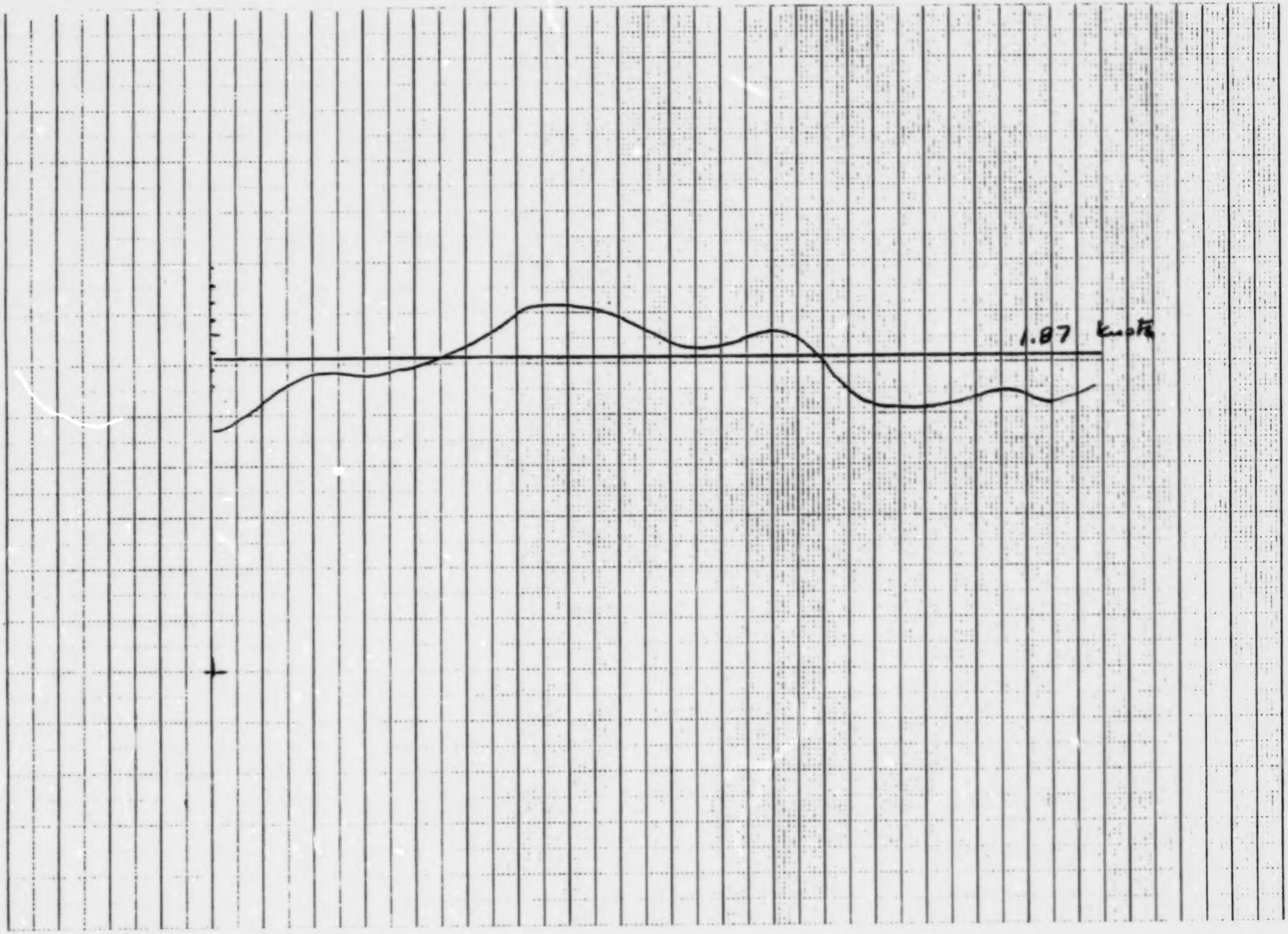


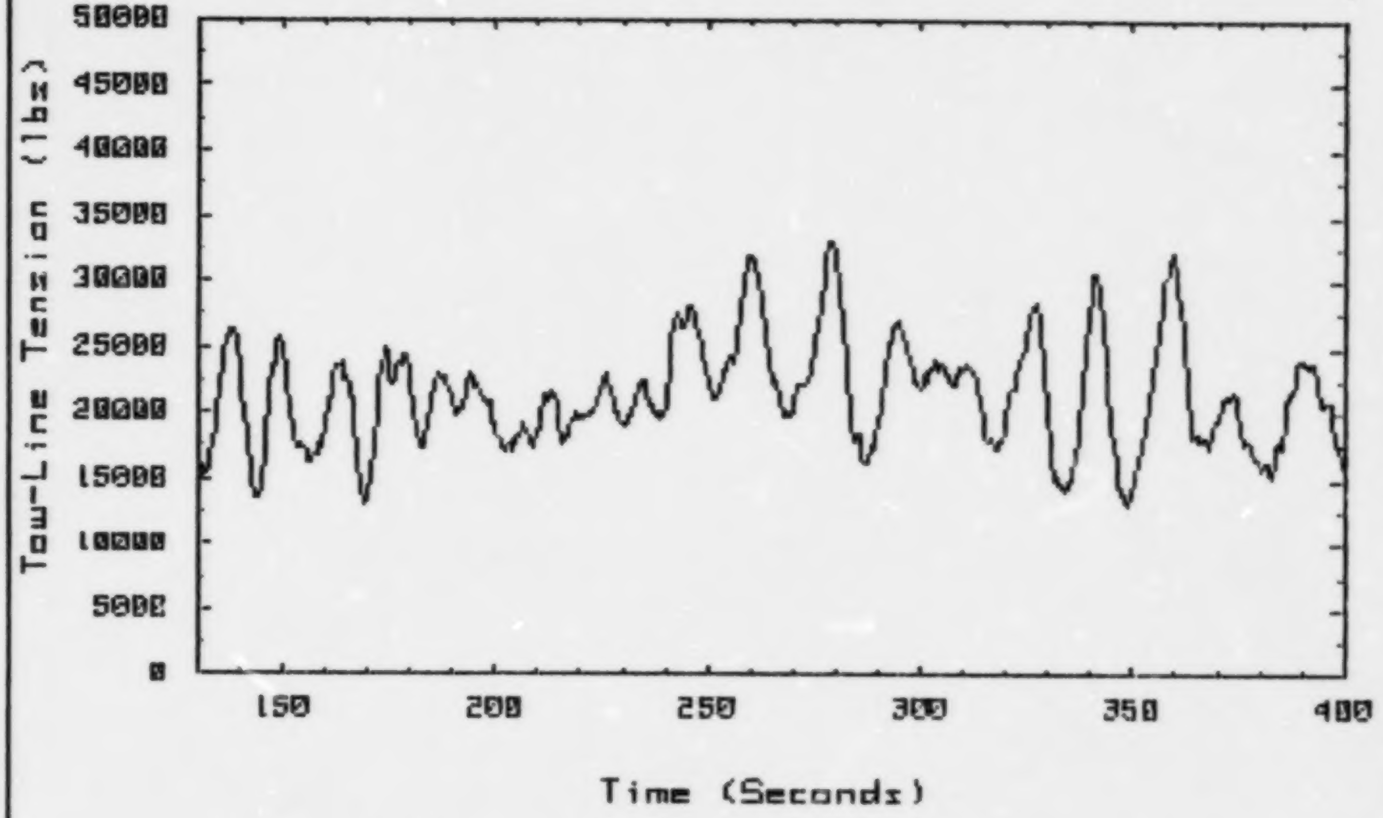
FULL-SCALE TOWED RESISTANCE TEST
TOW 4



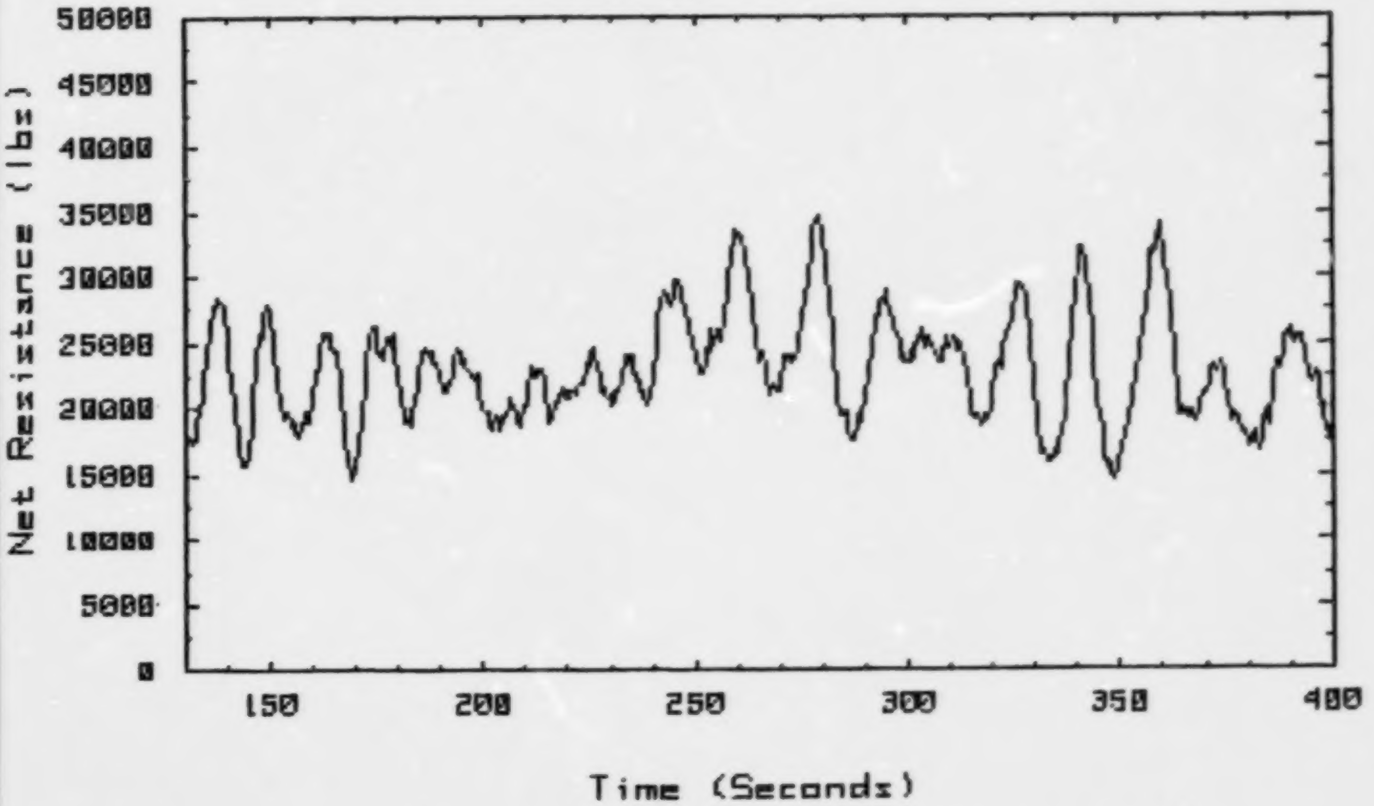
FULL-SCALE TOWED RESISTANCE TEST
TOW 4

K-E 10 X 10 TO THE CENTIMETER
461510





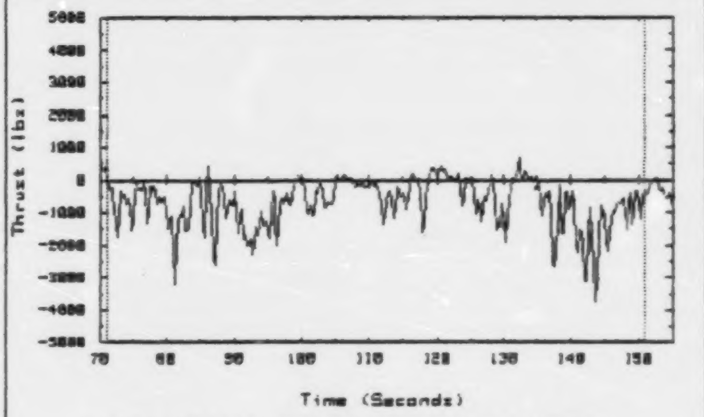
FULL-SCALE TOWED RESISTANCE TEST
TOW 4



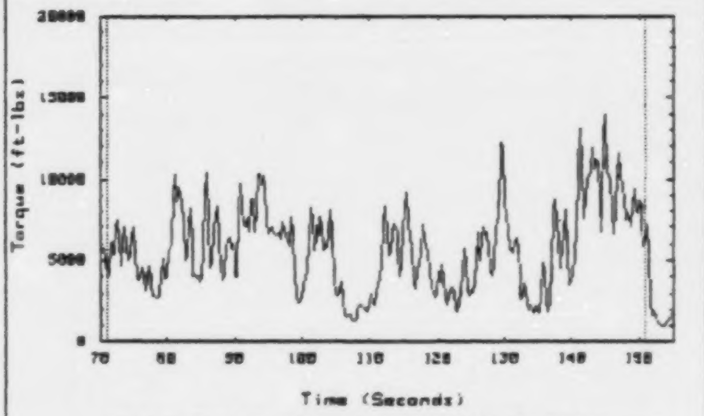
FULL-SCALE TOWED RESISTANCE TEST
TOW 4

```
Test Results for Test TOW_5:  02/21/86, 14:48:57
            For the Interval Between  71  sec and  151  sec

  CHANNEL                          MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                     673.6     -3731.1      -690.3        736.2
 2  Torque (ft-lbs)                13956.5      1294.1      5760.8       2551.5
 3  RPM (rpm)                         69.3        44.3        58.2          3.7
 4  Ship Speed (kts)                   6.9         3.0         4.8           .4
 5  Tow-Line Tension (lbs)         43371.0     28564.0     36876.5       3382.0
 6  Net Resistance (lbs)           43334.2     27532.5     36186.2       3355.3
```

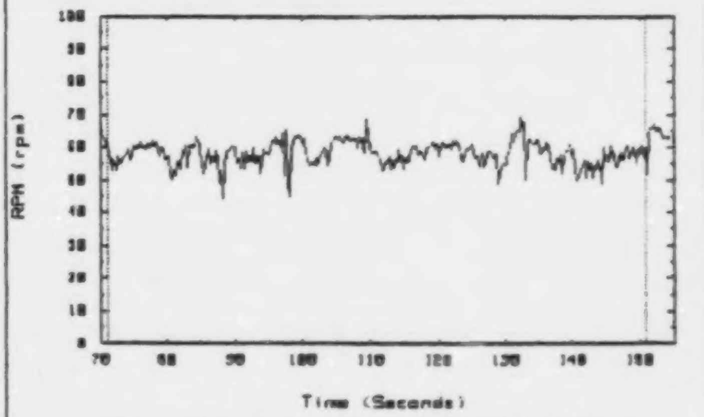
```
            Test Results for Test TOW_5:  02/21/86, 14:48:57
            For the Interval Between  71  sec and  151  sec

           Average Ship Speed                  4.8    kts
           Average Thrust                   -690.3    lbs
           Average Torque                   5760.8    ft-lbs
           Average RPM                        58.2    RPM
           Average Tow-Line Tension        36876.5    lbs
           Average Net Resistance          36186.2    lbs
```



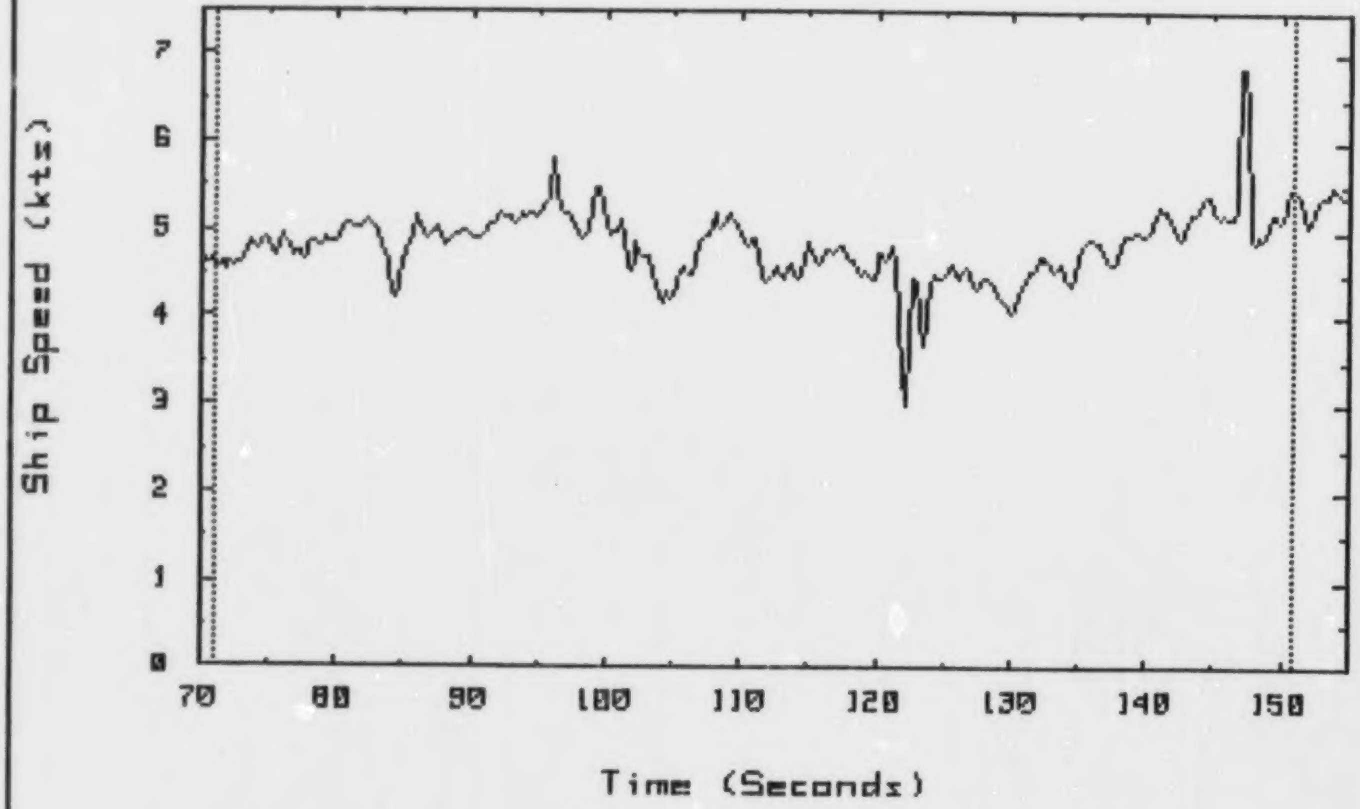
FULL-SCALE TOWED RESISTANCE TEST
TOW 5



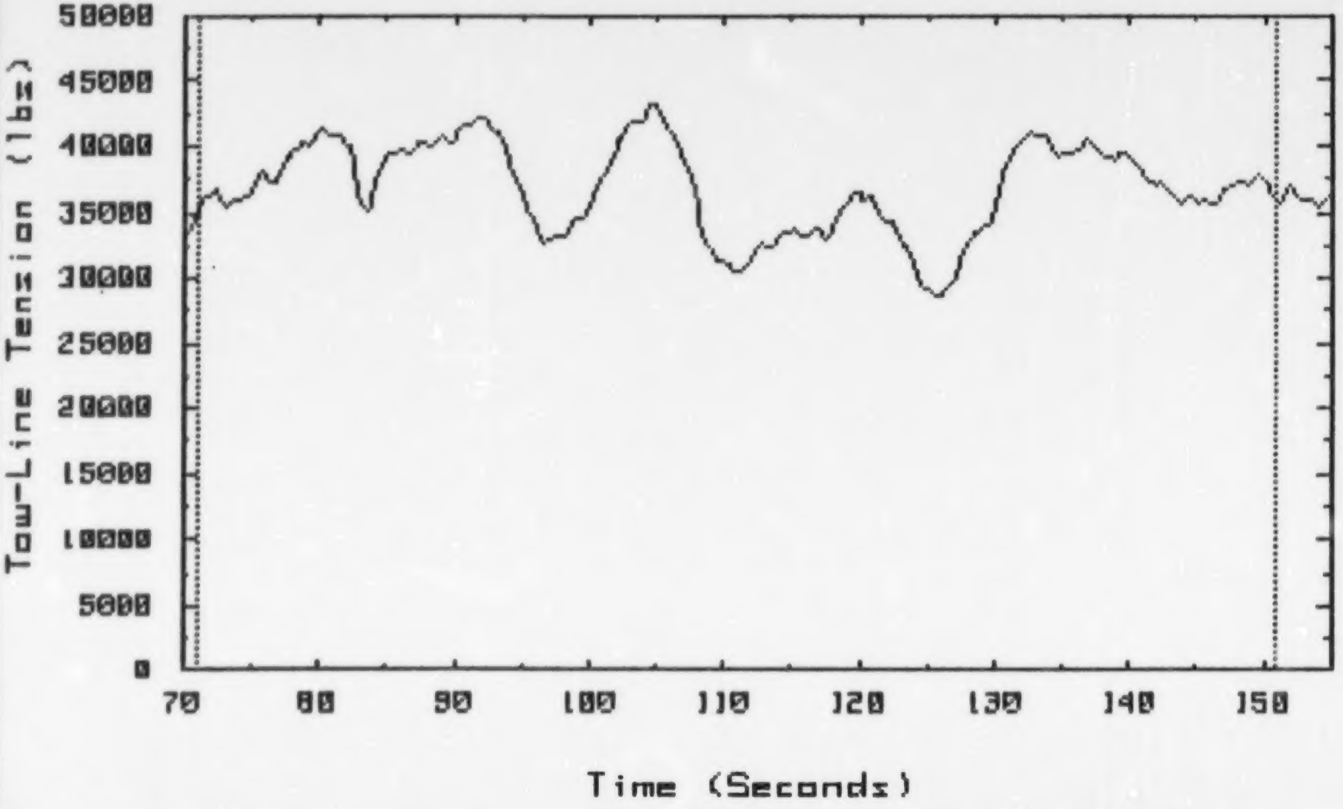
FULL-SCALE TOWED RESISTANCE TEST
TOW 5



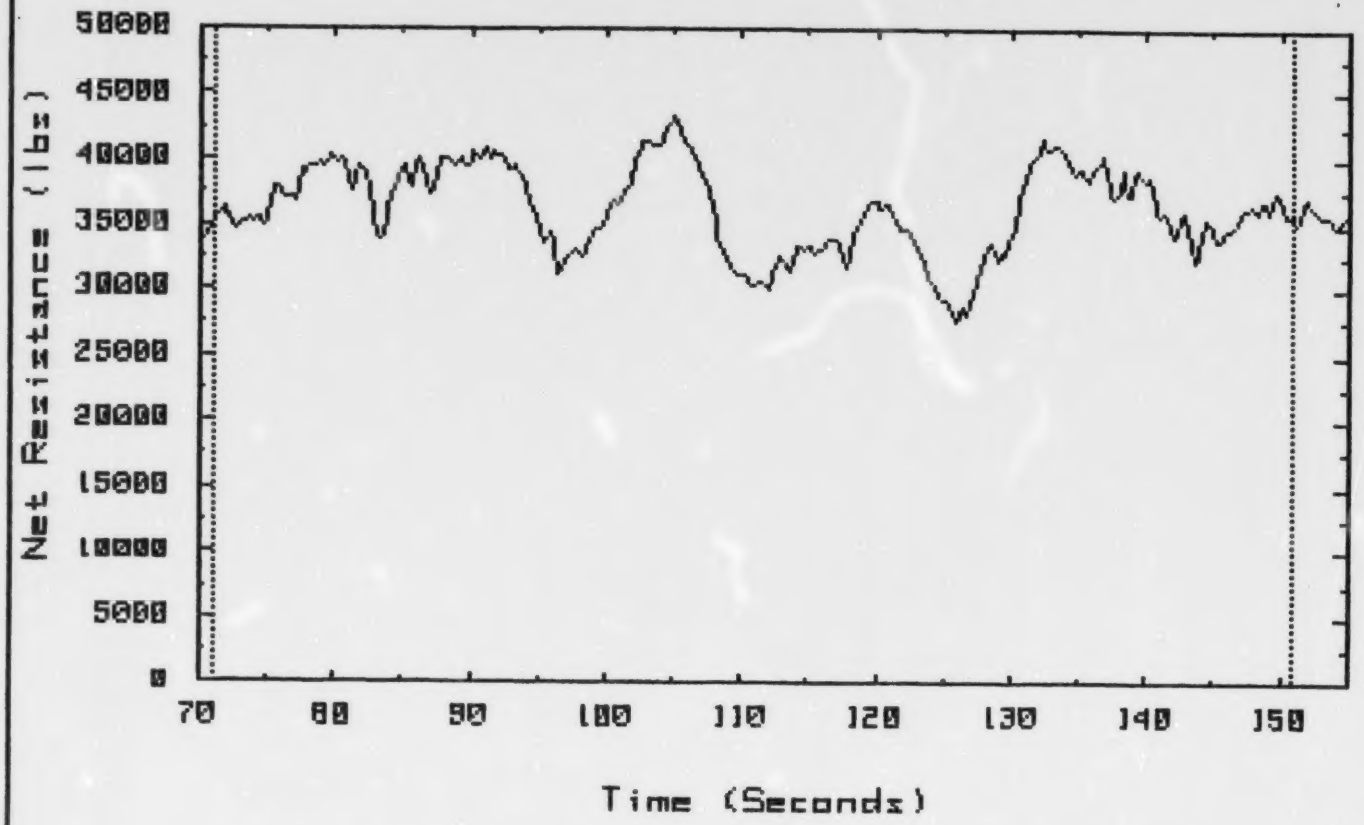
FULL-SCALE TOWED RESISTANCE TEST
TOW 5



FULL-SCALE TOWED RESISTANCE TEST
TOW 5

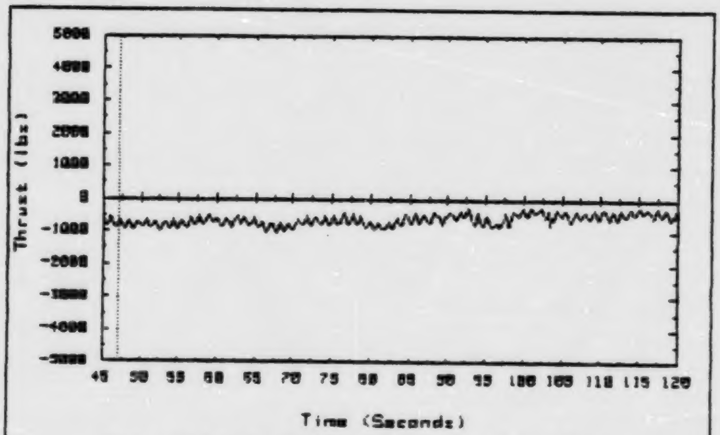


FULL-SCALE TOWED RESISTANCE TEST
TOW 5

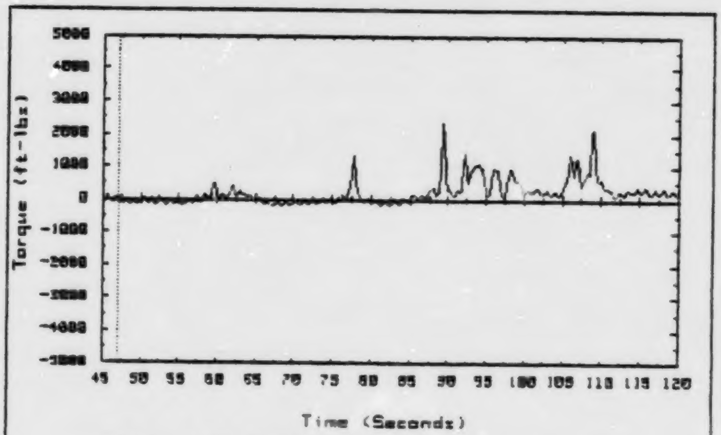


FULL-SCALE TOWED RESISTANCE TEST
TOW 5

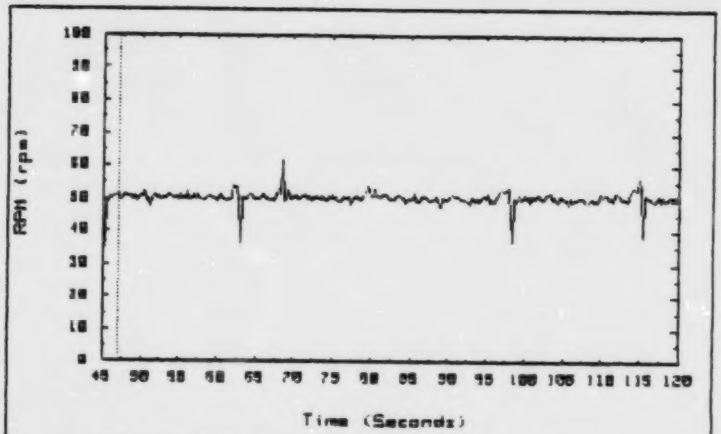
```
Test Results for Test TOW_6:  02/21/86, 16:59:15
              For the Interval Between  47  sec and  120  sec

   CHANNEL                              MAXIMUM     MINIMUM       MEAN     STDRD DEV

 1  Thrust (lbs)                         -231.9     -1037.1     -616.3        191.1
 2  Torque (ft-lbs)                      2330.6      -207.3      236.1        398.4
 3  RPM (rpm)                              61.7        36.3       50.5          1.9
 4  Ship Speed (kts)                        4.3         3.2        3.7           .2
 5  Tow-Line Tension (lbs)              23023.6      9056.6    15151.0       2903.7
 6  Net Resistance (lbs)                22507.5      8209.0    14534.7       2874.9

              Test Results for Test TOW_6:  02/21/86, 16:59:15
              For the Interval Between  47  sec and  120  sec

             Average Ship Speed                 3.7   kts
             Average Thrust                  -616.3   lbs
             Average Torque                   236.1   ft-lbs
             Average RPM                       50.5   RPM
             Average Tow-Line Tension       15151.0   lbs
             Average Net Resistance         14534.7   lbs
```



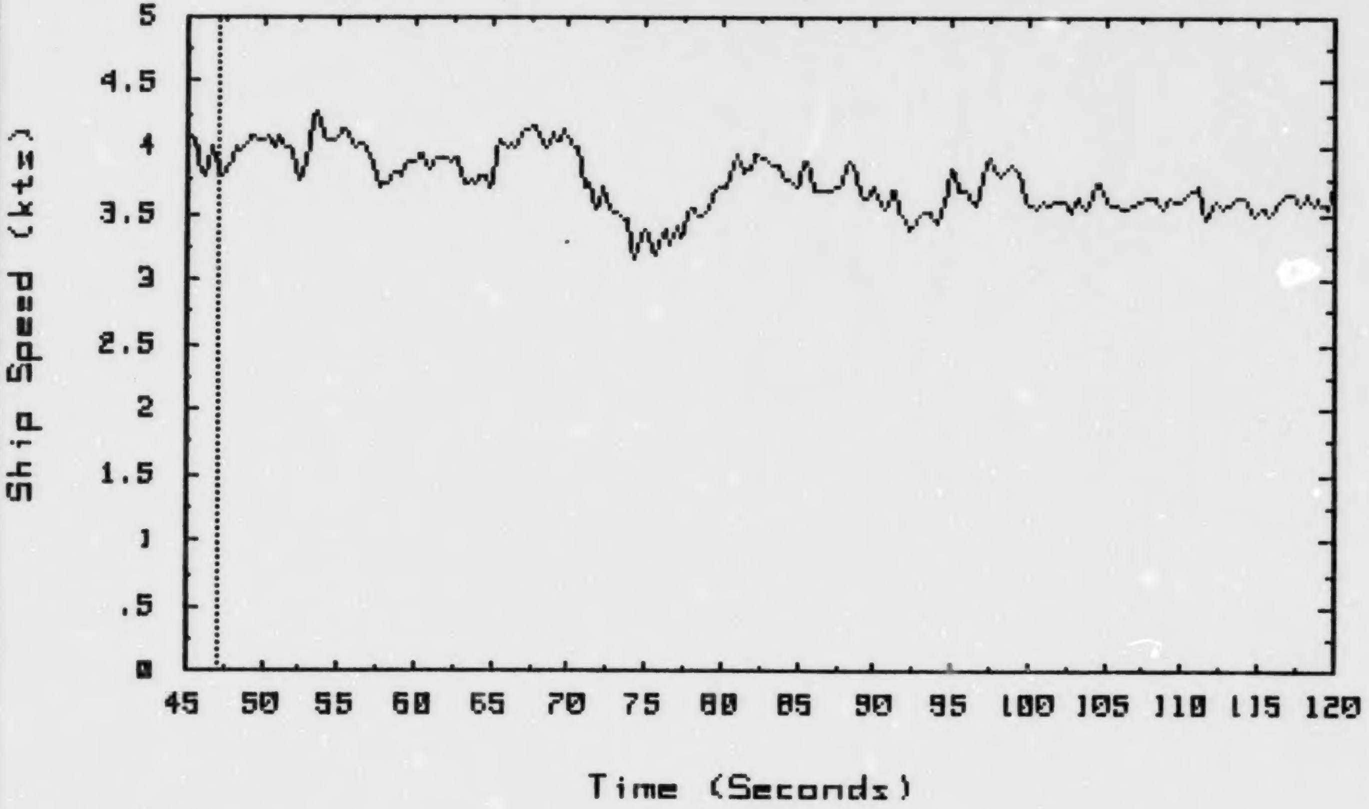
FULL-SCALE TOWED RESISTANCE TEST
TOW 6



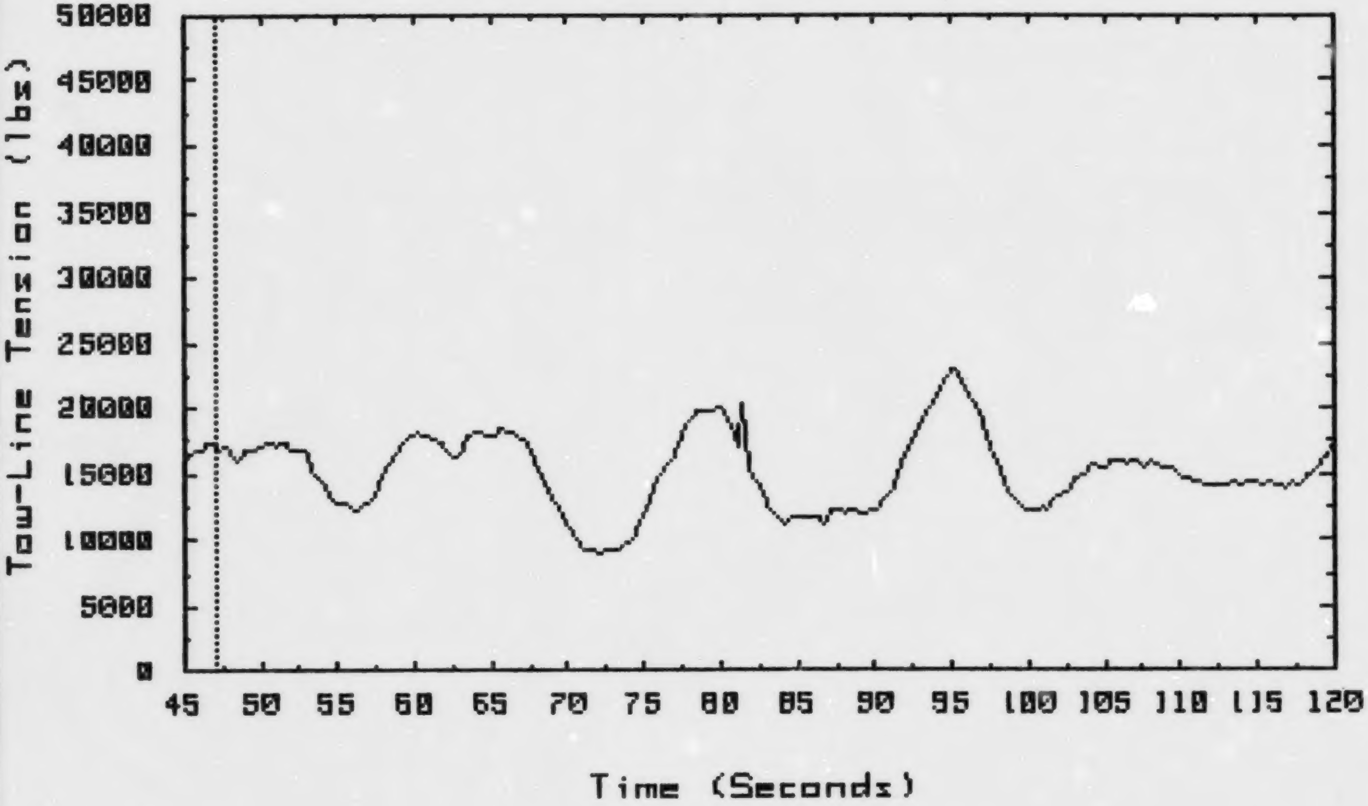
FULL-SCALE TOWED RESISTANCE TEST
TOW 6



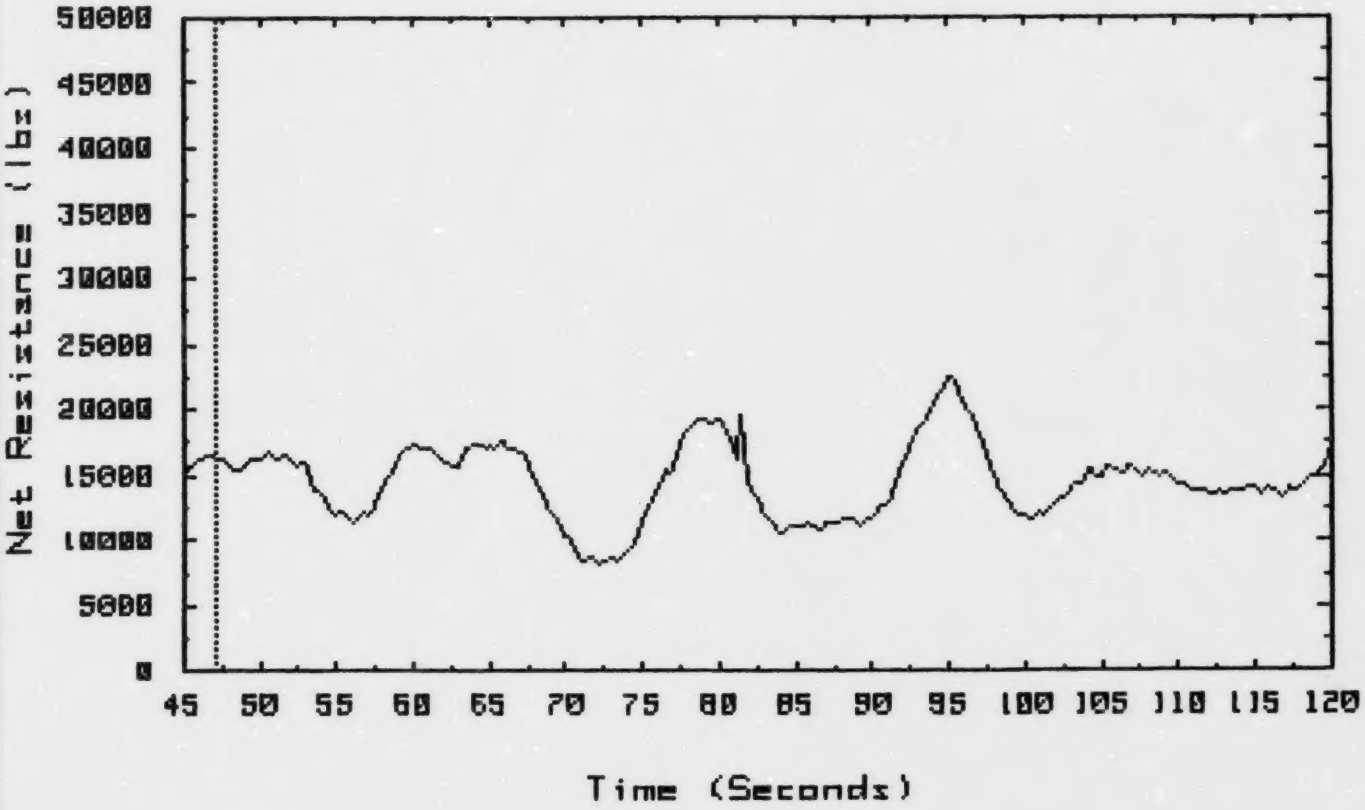
FULL-SCALE TOWED RESISTANCE TEST
TOW 6



FULL-SCALE TOWED RESISTANCE TEST
TOW 6

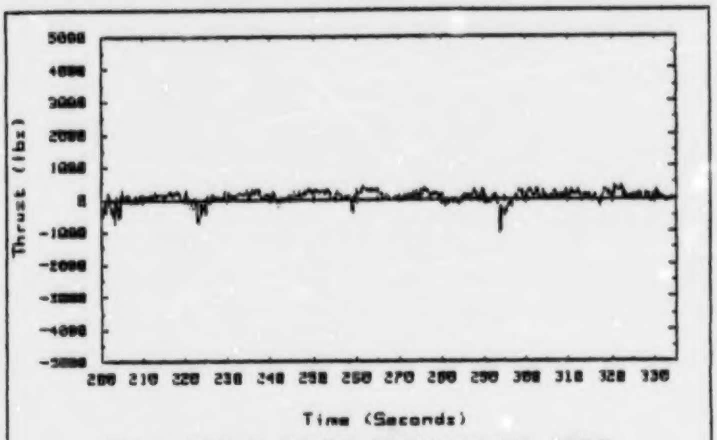


FULL-SCALE TOWED RESISTANCE TEST
TOW 6

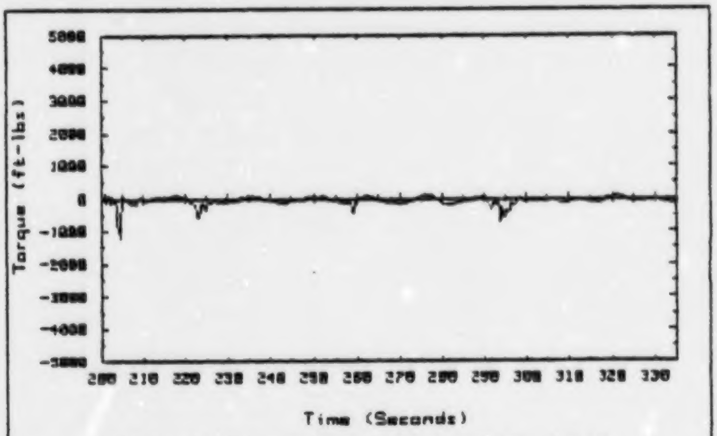


FULL-SCALE TOWED RESISTANCE TEST
TOW 6

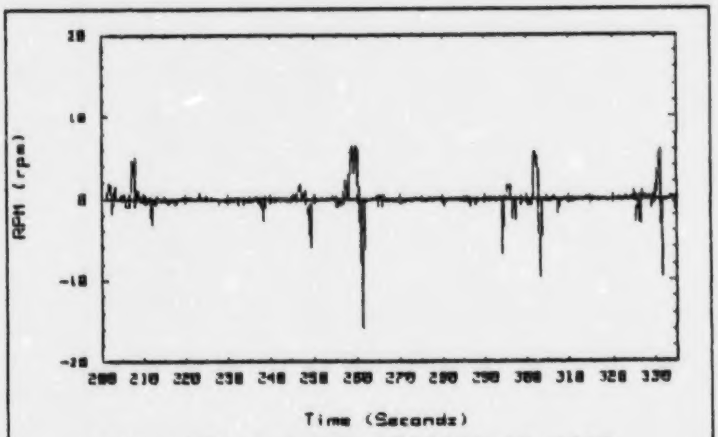
```
Test Results for Test TOW_7:  02/22/86, 15:13:12
          For the Interval Between  200  sec and  335  sec

  CHANNEL                        MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                   421.7     -1044.5       66.7        179.4
 2  Torque (ft-lbs)                161.6     -1229.1      -60.8        126.8
 3  RPM (rpm)                        6.3       -15.7        -.1          1.5
 4  Ship Speed (kts)                 3.3         2.5        2.8           .1
 5  Tow-Line Tension (lbs)       29679.1      7165.4    18302.0       4784.5
 6  Net Resistance (lbs)         29817.1      7208.7    18368.7       4771.5

          Test Results for Test TOW_7:  02/22/86, 15:13:12
          For the Interval Between  200  sec and  335  sec

         Average Ship Speed                2.8   kts
         Average Thrust                   66.7   lbs
         Average Torque                  -60.8   ft-lbs
         Average RPM                       -.1   RPM
         Average Tow-Line Tension      18302.0   lbs
         Average Net Resistance        18368.7   lbs
```



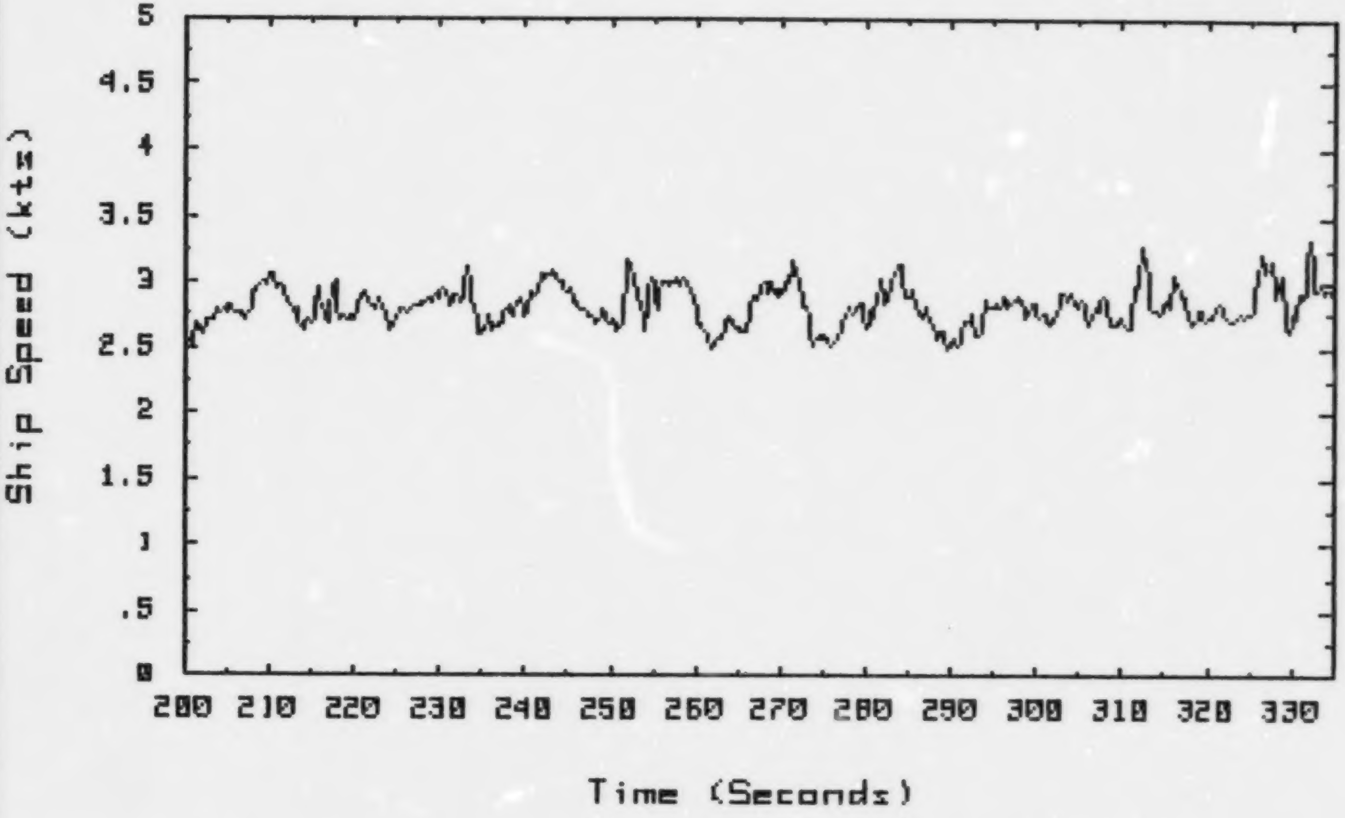
FULL-SCALE TOWED RESISTANCE TEST
TOW 7



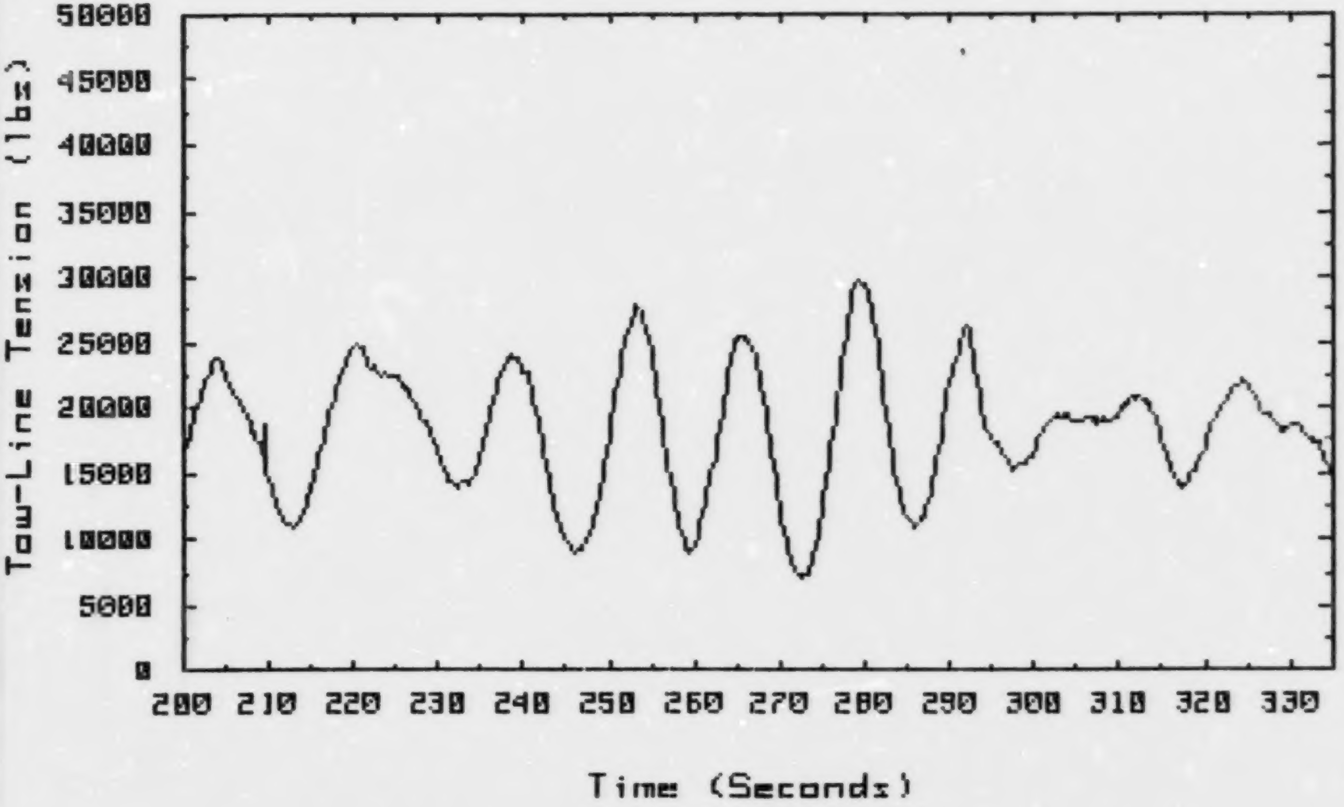
FULL-SCALE TOWED RESISTANCE TEST
TOW 7



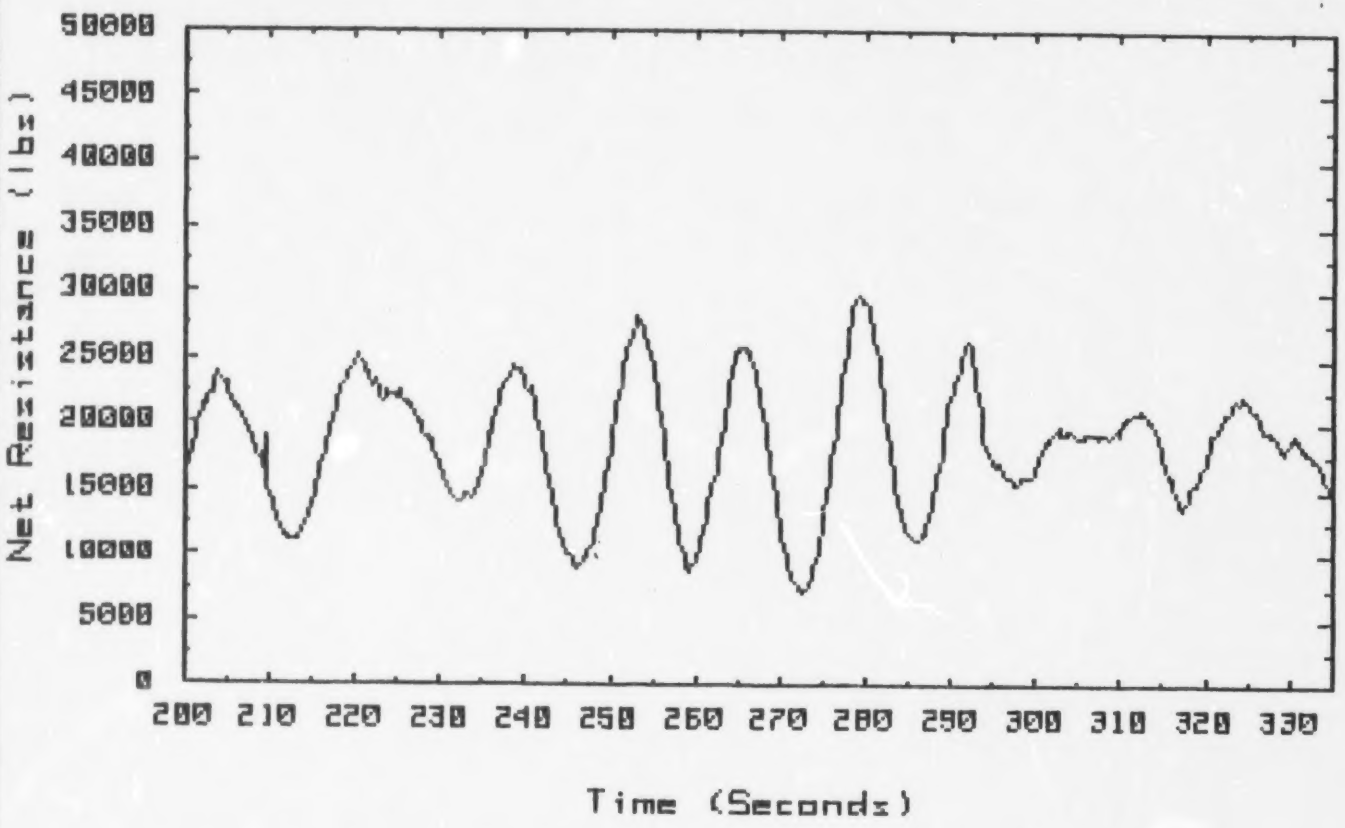
FULL-SCALE TOWED RESISTANCE TEST
TOW 7



FULL-SCALE TOWED RESISTANCE TEST
TOW 7

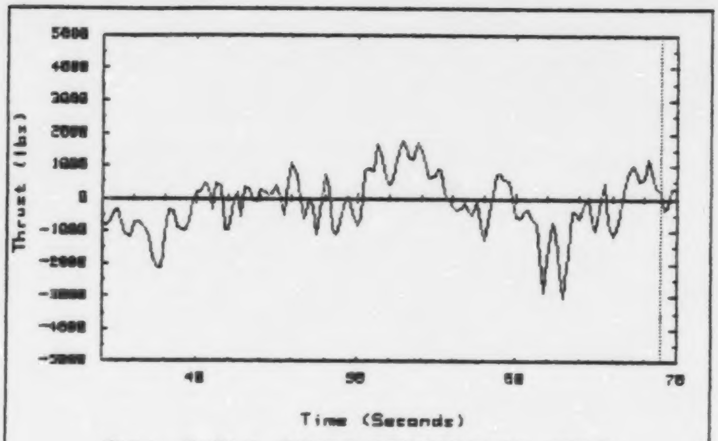


FULL-SCALE TOWED RESISTANCE TEST
TOW 7

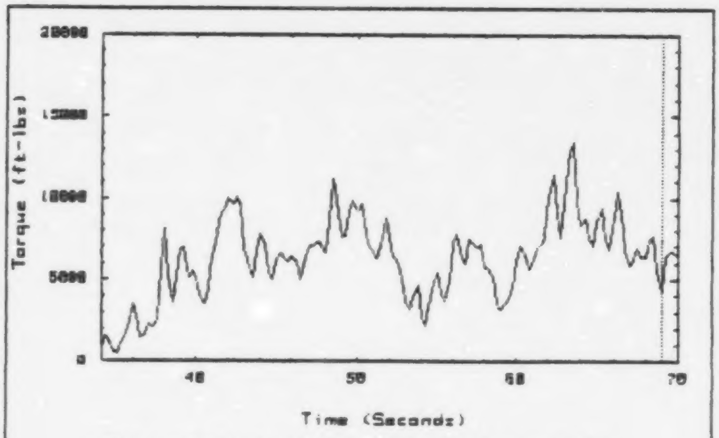


FULL-SCALE TOWED RESISTANCE TEST
TOW 7

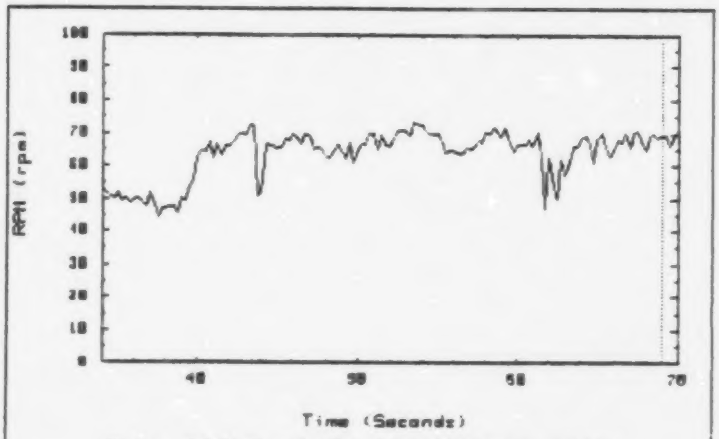
```
Test Results for Test TOW_8:  02/22/86, 17:21:21
          For the Interval Between  34  sec and  69  sec

  CHANNEL                            MAXIMUM    MINIMUM      MEAN     STDRD DEV

1  Thrust (lbs)                       1763.3    -3013.8    -164.9       889.8
2  Torque (ft-lbs)                   13440.0      496.4    6271.4      2530.4
3  RPM (rpm)                            73.3       44.6      63.5         7.5
4  Ship Speed (kts)                      6.9        5.8       6.3          .2
5  Tow-Line Tension (lbs)            40770.0    23382.1   32164.8      4450.6
6  Net Resistance (lbs)              41392.2    23821.1   31999.9      4435.8

          Test Results for Test TOW_8:  02/22/86, 17:21:21
          For the Interval Between  34  sec and  69  sec

         Average Ship Speed                   6.3   kts
         Average Thrust                    -164.9   lbs
         Average Torque                    6271.4   ft-lbs
         Average RPM                         63.5   RPM
         Average Tow-Line Tension         32164.8   lbs
         Average Net Resistance           31999.9   lbs
```



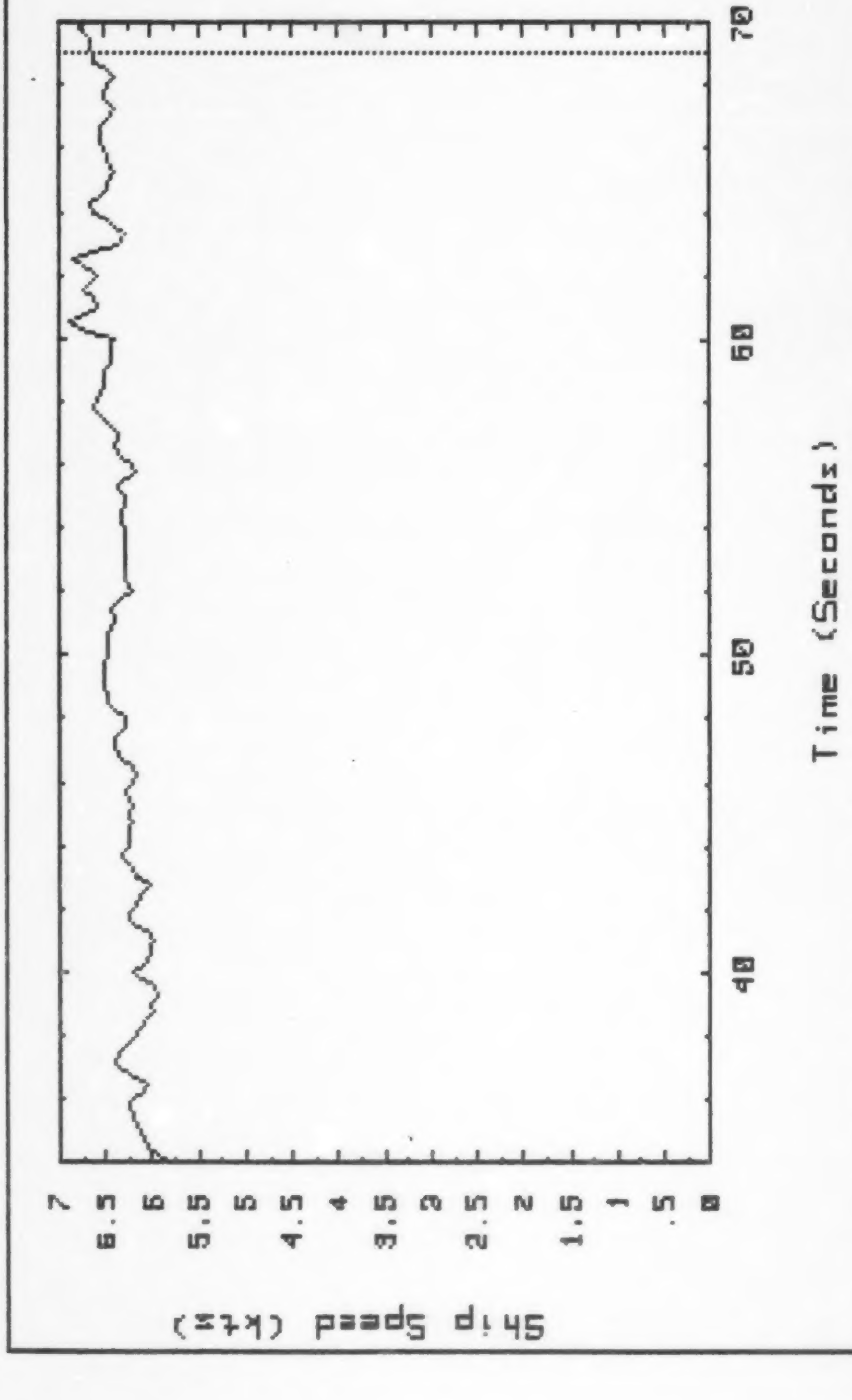
FULL-SCALE TOWED RESISTANCE TEST
TOW 8



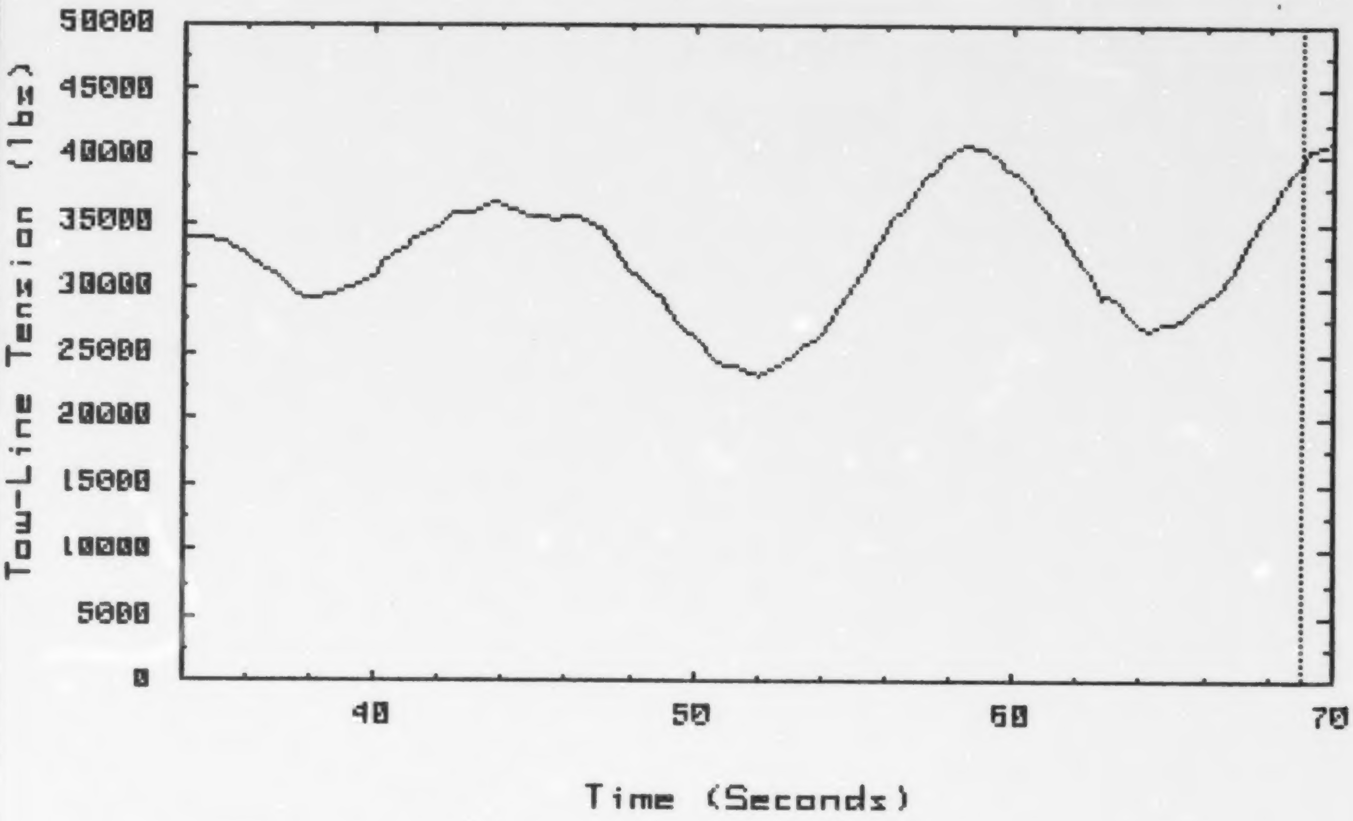
FULL-SCALE TOWED RESISTANCE TEST
TOW 8



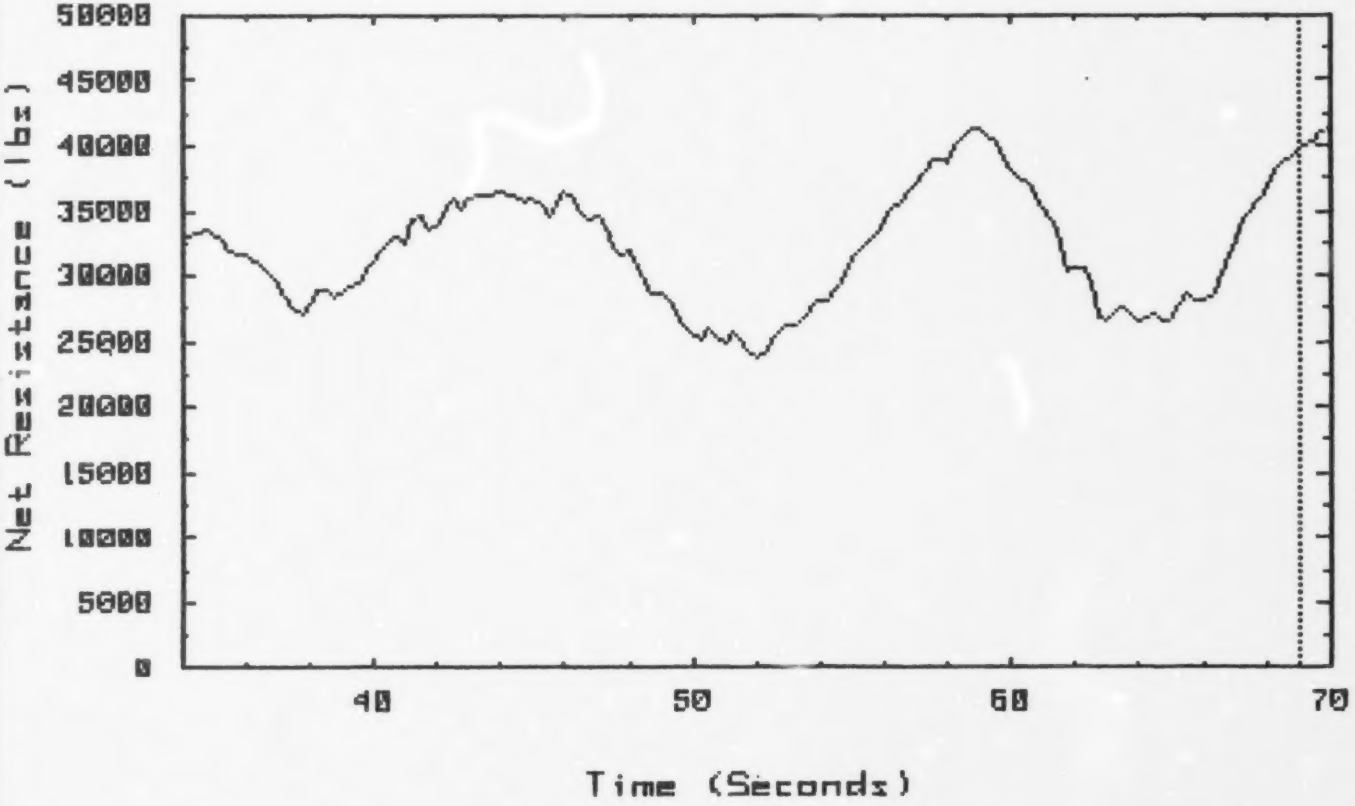
FULL-SCALE TOWED RESISTANCE TEST
TOW 8



FULL-SCALE TOWED RESISTANCE TEST
TOW 8

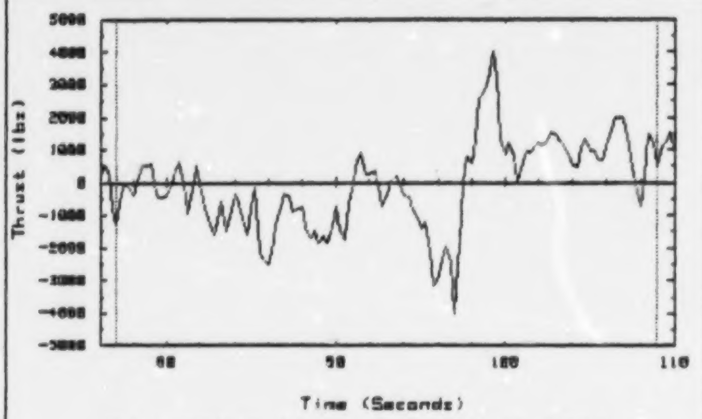


FULL-SCALE TOWED RESISTANCE TEST
TOW 8

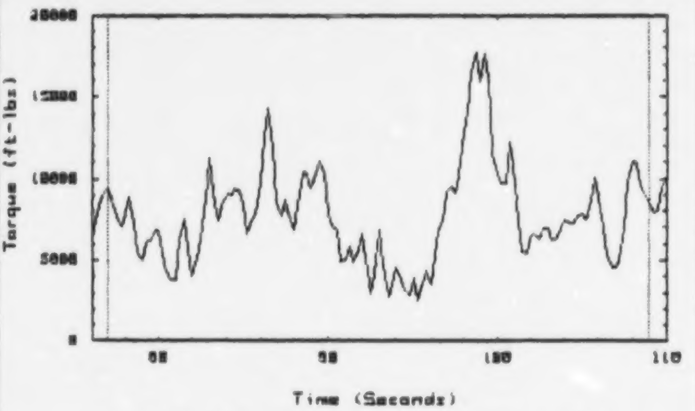


FULL-SCALE TOWED RESISTANCE TEST
TOW 8

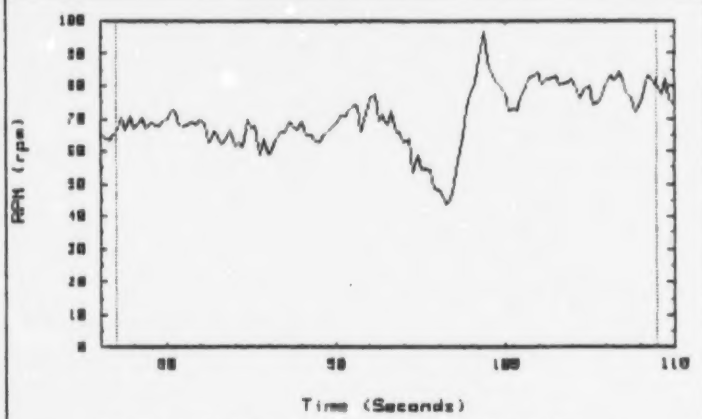
```
Test Results for Test TOW_8:  02/22/86, 17:21:21
            For the Interval Between  77  sec and  109  sec

  CHANNEL                              MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                        4033.5     -4007.1     -102.6       1347.8
 2  Torque (ft-lbs)                    17719.0      2528.8     7748.1       3056.3
 3  RPM (rpm)                             96.6        44.1       70.4          9.4
 4  Ship Speed (kts)                       6.9         6.5        6.8           .1
 5  Tow-Line Tension (lbs)             39362.9     25593.3    33426.7       3627.2
 6  Net Resistance (lbs)               40558.6     25098.1    33324.1       3879.5

             Test Results for Test TOW_8:  02/22/86, 17:21:21
             For the Interval Between  77  sec and  109  sec

            Average Ship Speed                  6.8   kts
            Average Thrust                   -102.6   lbs
            Average Torque                   7748.1   ft-lbs
            Average RPM                        70.4   RPM
            Average Tow-Line Tension        33426.7   lbs
            Average Net Resistance          33324.1   lbs
```



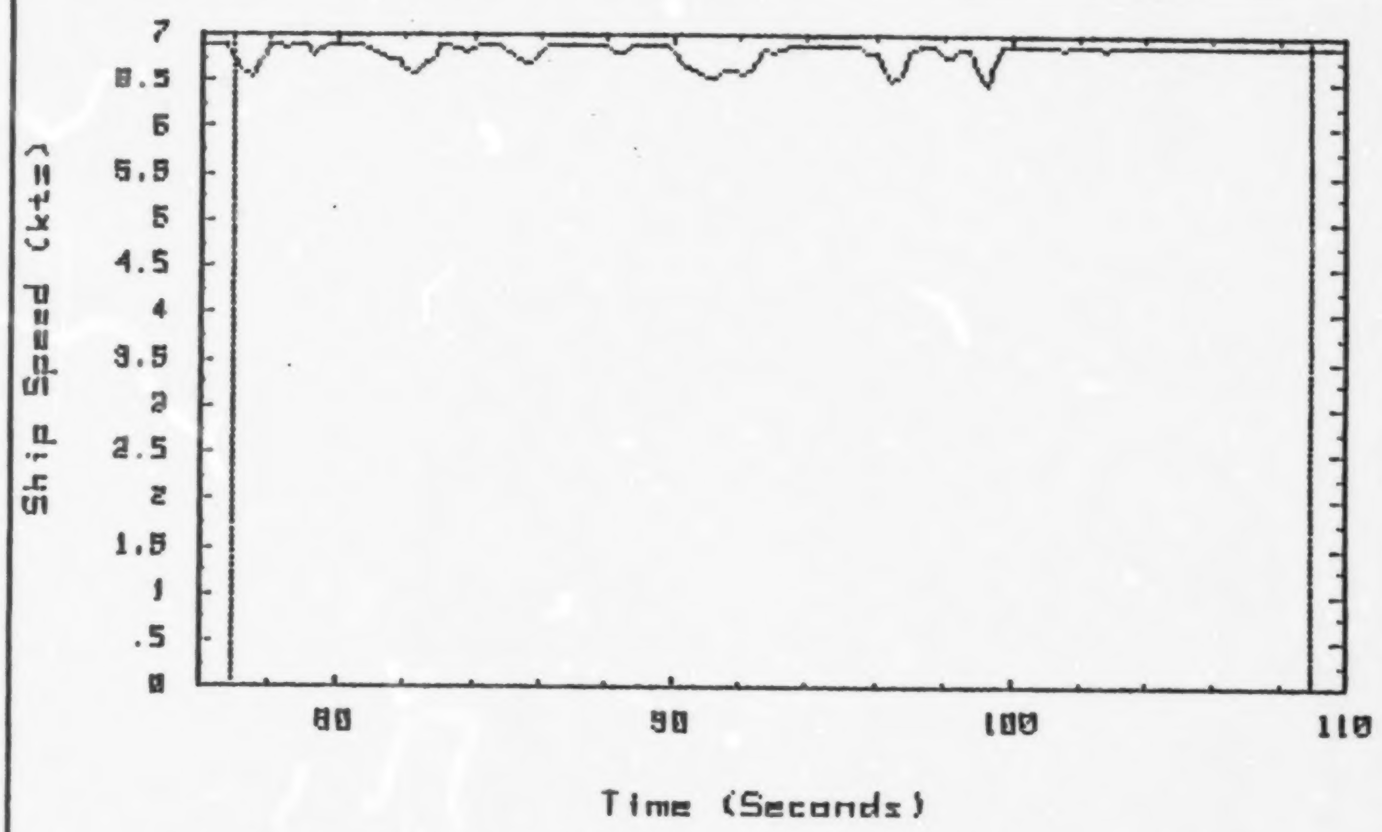
FULL-SCALE TOWED RESISTANCE TEST
TOW 8



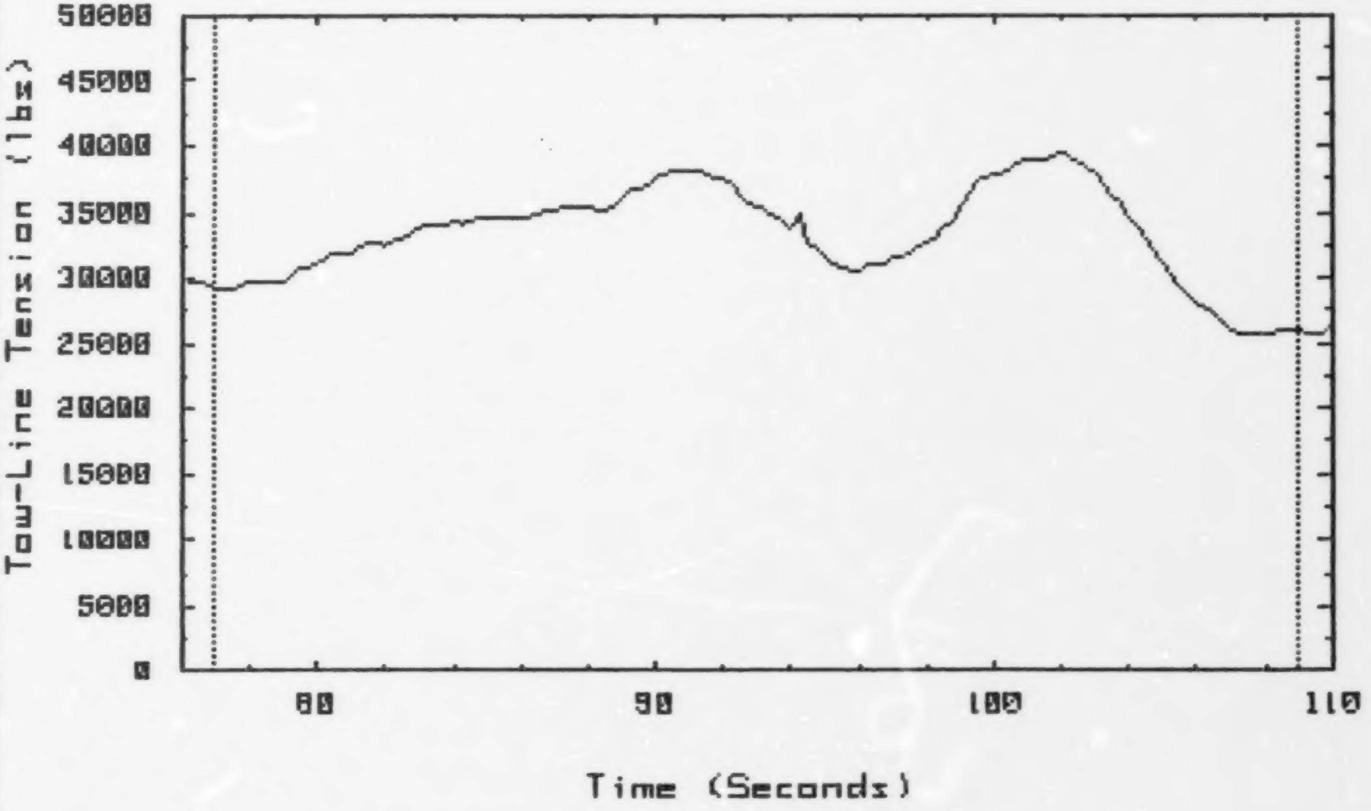
FULL-SCALE TOWED RESISTANCE TEST
TOW 8



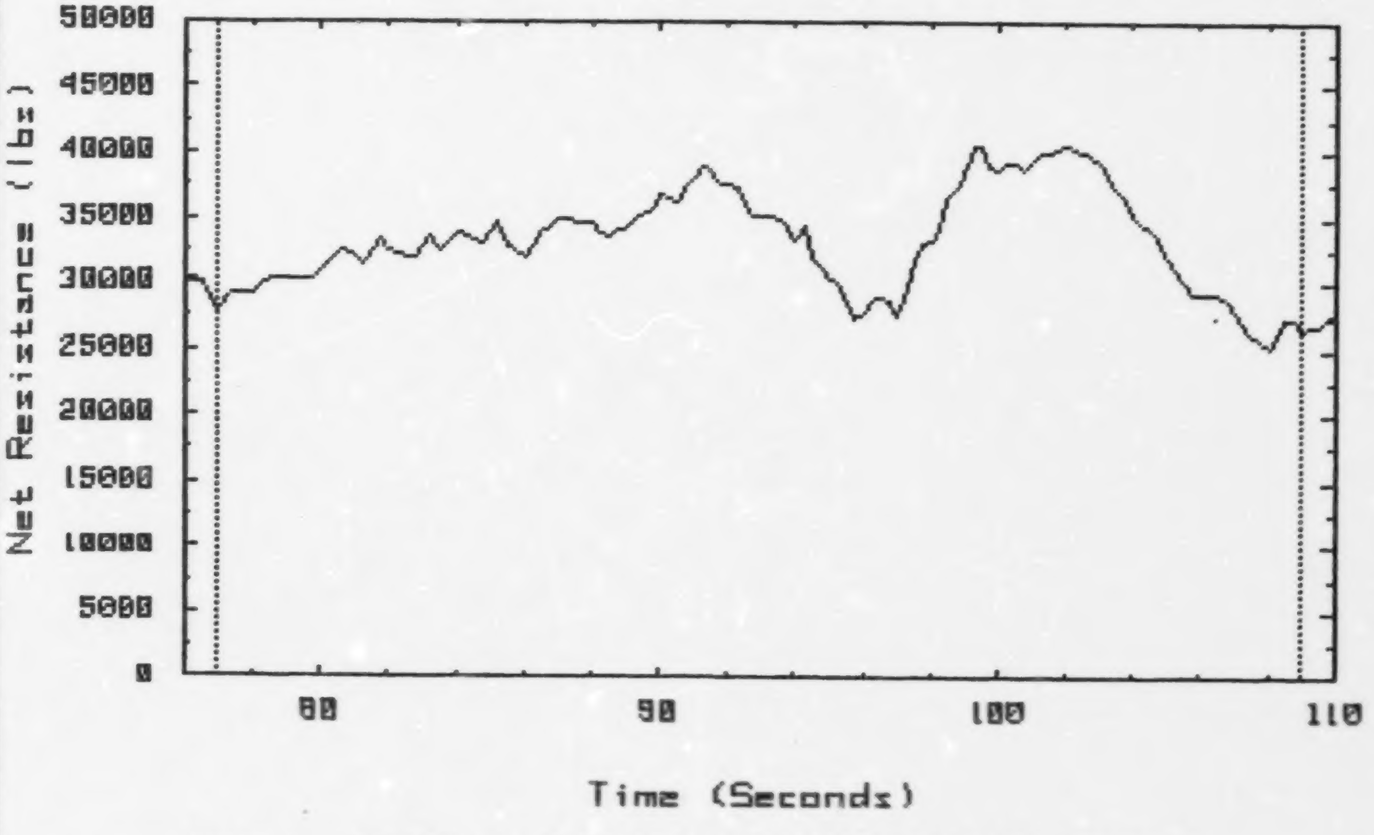
FULL-SCALE TOWED RESISTANCE TEST
TOW 8



FULL-SCALE TOWED RESISTANCE TEST
TOW 8

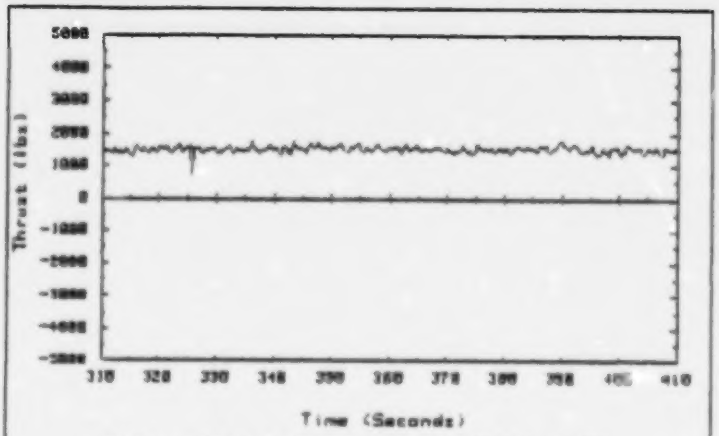


FULL-SCALE TOWED RESISTANCE TEST
TOW 8

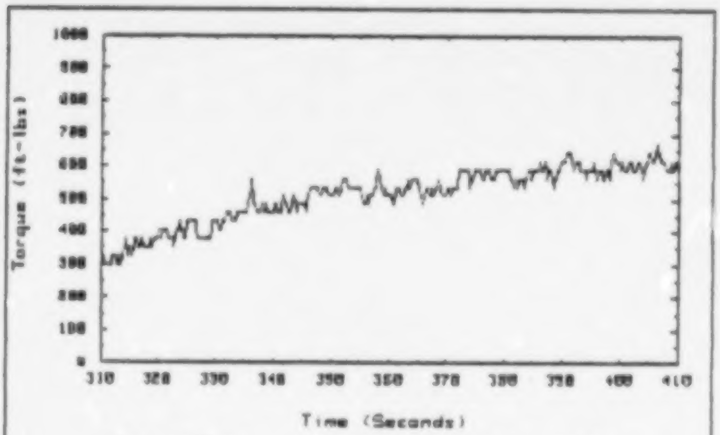


FULL-SCALE TOWED RESISTANCE TEST
TOW 8

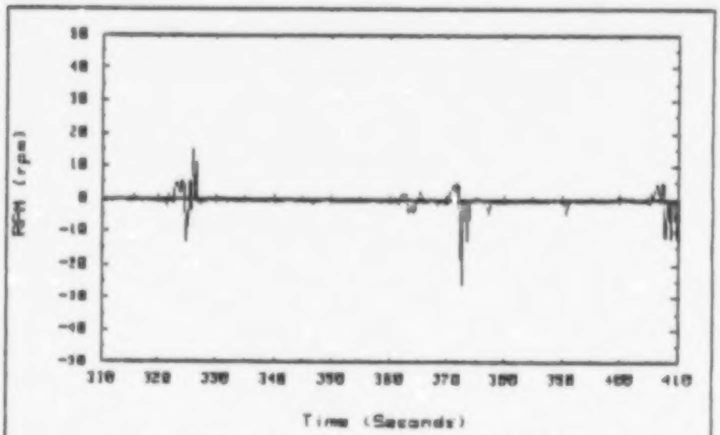
```
Test Results for Test TOW_9:  02/22/86, 10:03:58
           For the Interval Between  310  sec and  410  sec

  CHANNEL                              MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                        1760.8       720.2      1517.3          97.5
 2  Torque (ft-lbs)                      672.2       297.8       512.6          89.2
 3  RPM (rpm)                             14.9       -26.2         -.5           2.6
 4  Ship Speed (kts)                       1.4          .9         1.1            .1
 5  Tow-Line Tension (lbs)             20864.5      9808.6     15188.2        2682.7
 6  Net Resistance (lbs)               22388.8     11238.3     16705.5        2662.9

            Test Results for Test TOW_9:  02/22/86, 10:03:58
            For the Interval Between  310  sec and  410  sec

           Average Ship Speed                   1.1   kts
           Average Thrust                    1517.3   lbs
           Average Torque                     512.6   ft-lbs
           Average RPM                          -.5   RPM
           Average Tow-Line Tension         15188.2   lbs
           Average Net Resistance           16705.5   lbs
```



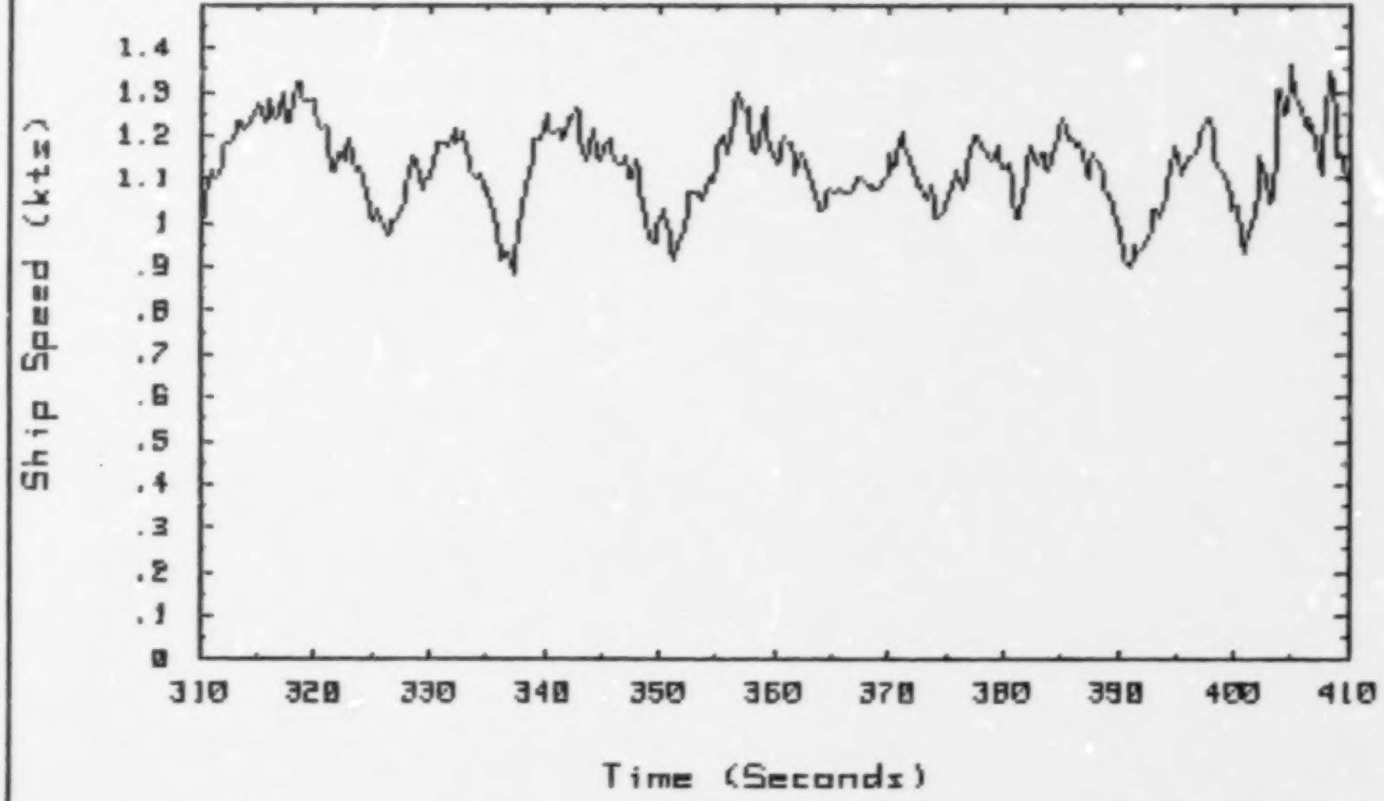
FULL-SCALE TOWED RESISTANCE TEST
TOW 3



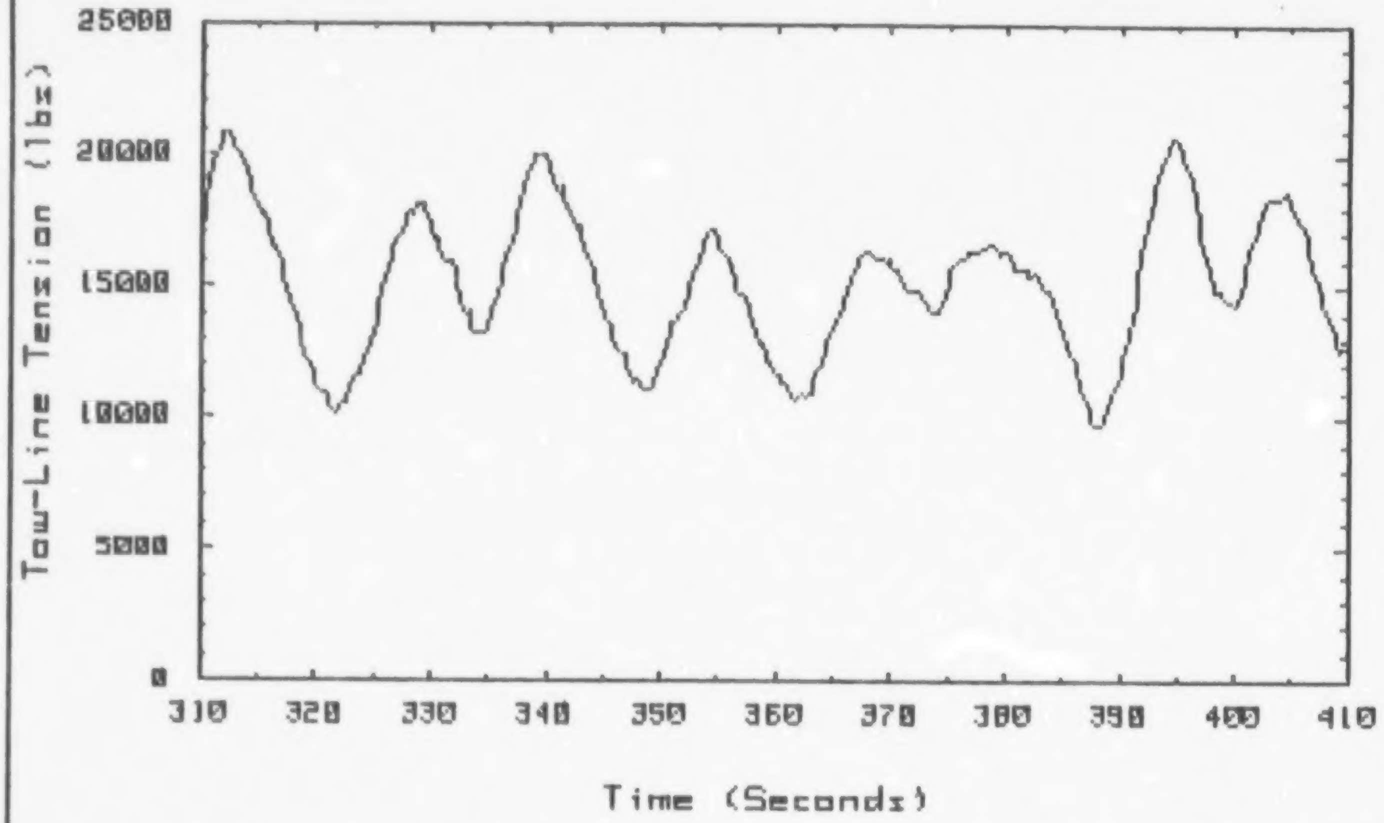
FULL-SCALE TOWED RESISTANCE TEST
TOW 3



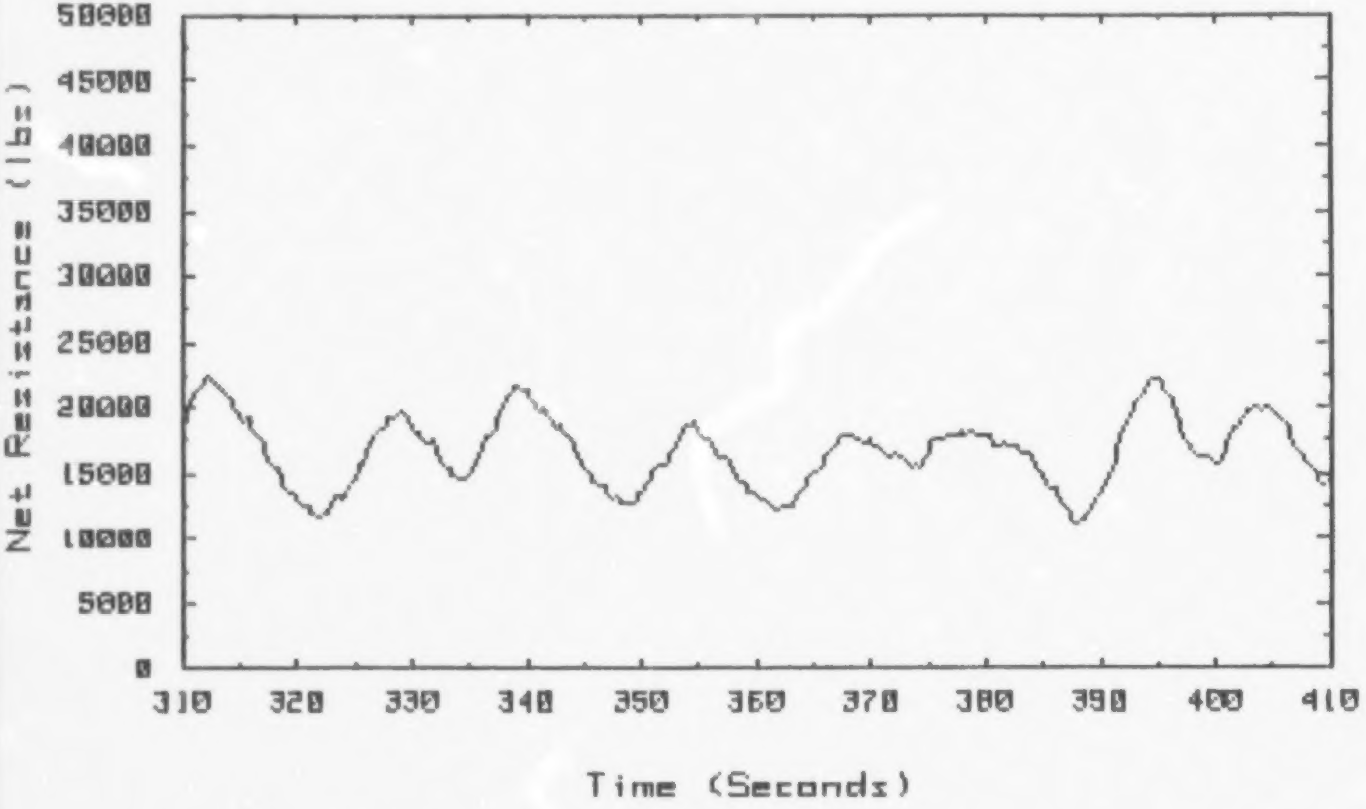
FULL-SCALE TOWED RESISTANCE TEST
TOW 3



FULL-SCALE TOWED RESISTANCE TEST
TOW 9

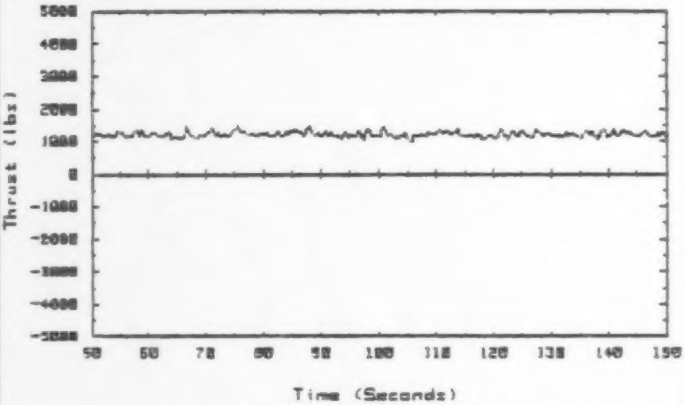


FULL-SCALE TOWED RESISTANCE TEST
TOW 9

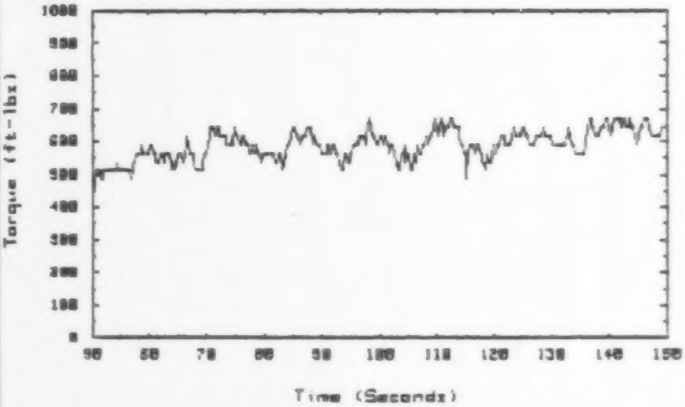


FULL-SCALE TOWED RESISTANCE TEST
TOW 9

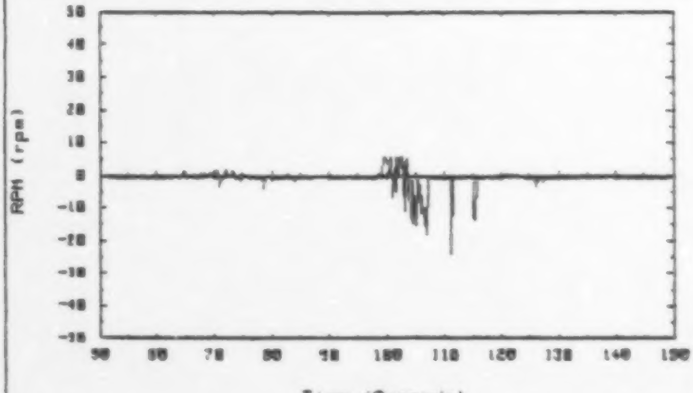
```
Test Results for Test TOW_9A:  02/22/86, 10:21:43
             For the Interval Between  50  sec and  150  sec

   CHANNEL                         MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                    1477.0      1004.0      1222.8          88.6
 2  Torque (ft-lbs)                  672.2       458.3       589.9          45.7
 3  RPM (rpm)                          6.0       -24.0         -.7           2.7
 4  Ship Speed (kts)                   1.7         1.0         1.3            .2
 5  Tow-Line Tension (lbs)         26593.5      7195.4     14520.2        4996.3
 6  Net Resistance (lbs)           27833.9      8435.9     15743.0        4986.8

             Test Results for Test TOW_9A:  02/22/86, 10:21:43
             For the Interval Between  50  sec and  150  sec

            Average Ship Speed                  1.3   kts
            Average Thrust                   1222.8   lbs
            Average Torque                    589.9   ft-lbs
            Average RPM                         -.7   RPM
            Average Tow-Line Tension        14520.2   lbs
            Average Net Resistance          15743.0   lbs
```



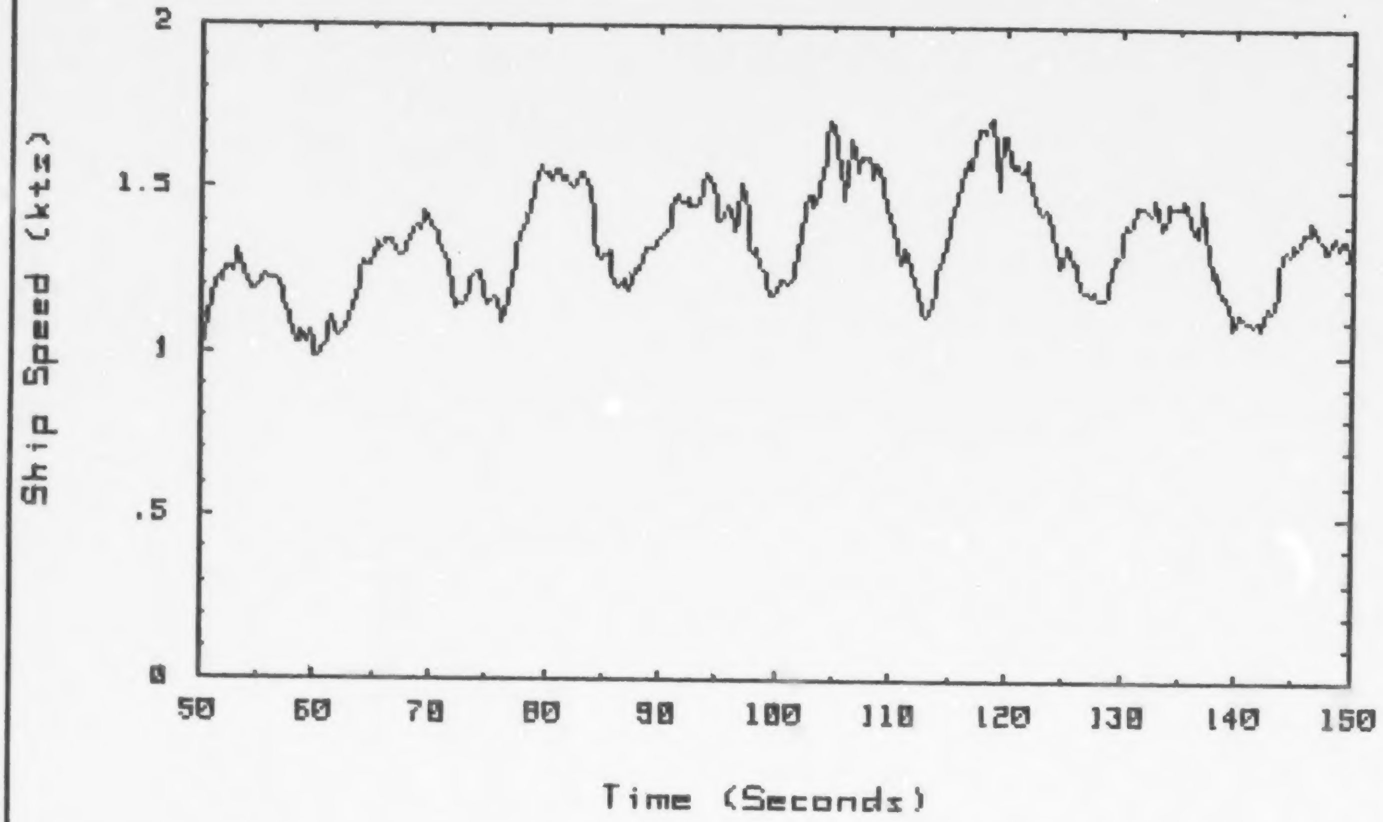
FULL-SCALE TOWED RESISTANCE TEST
TOW 9



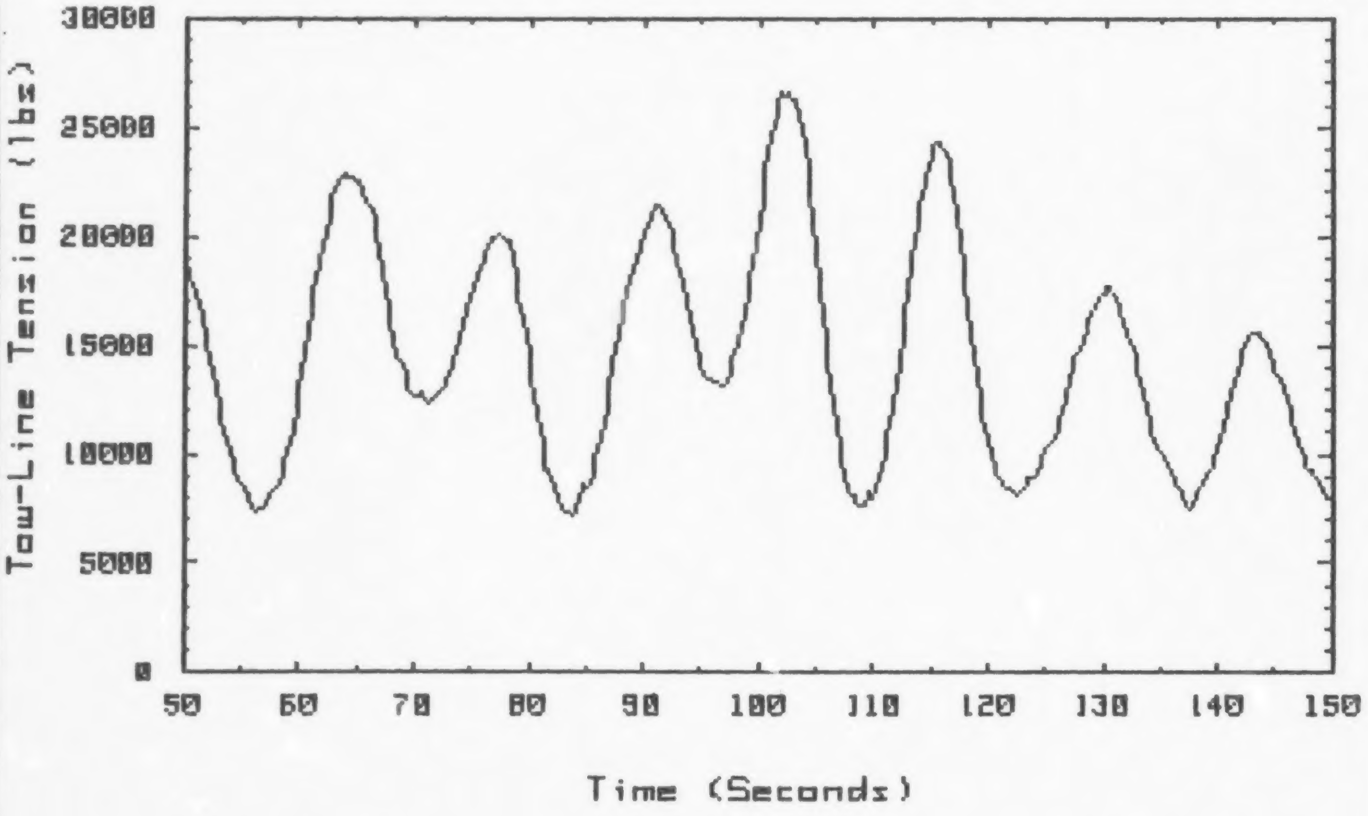
FULL-SCALE TOWED RESISTANCE TEST
TOW 9



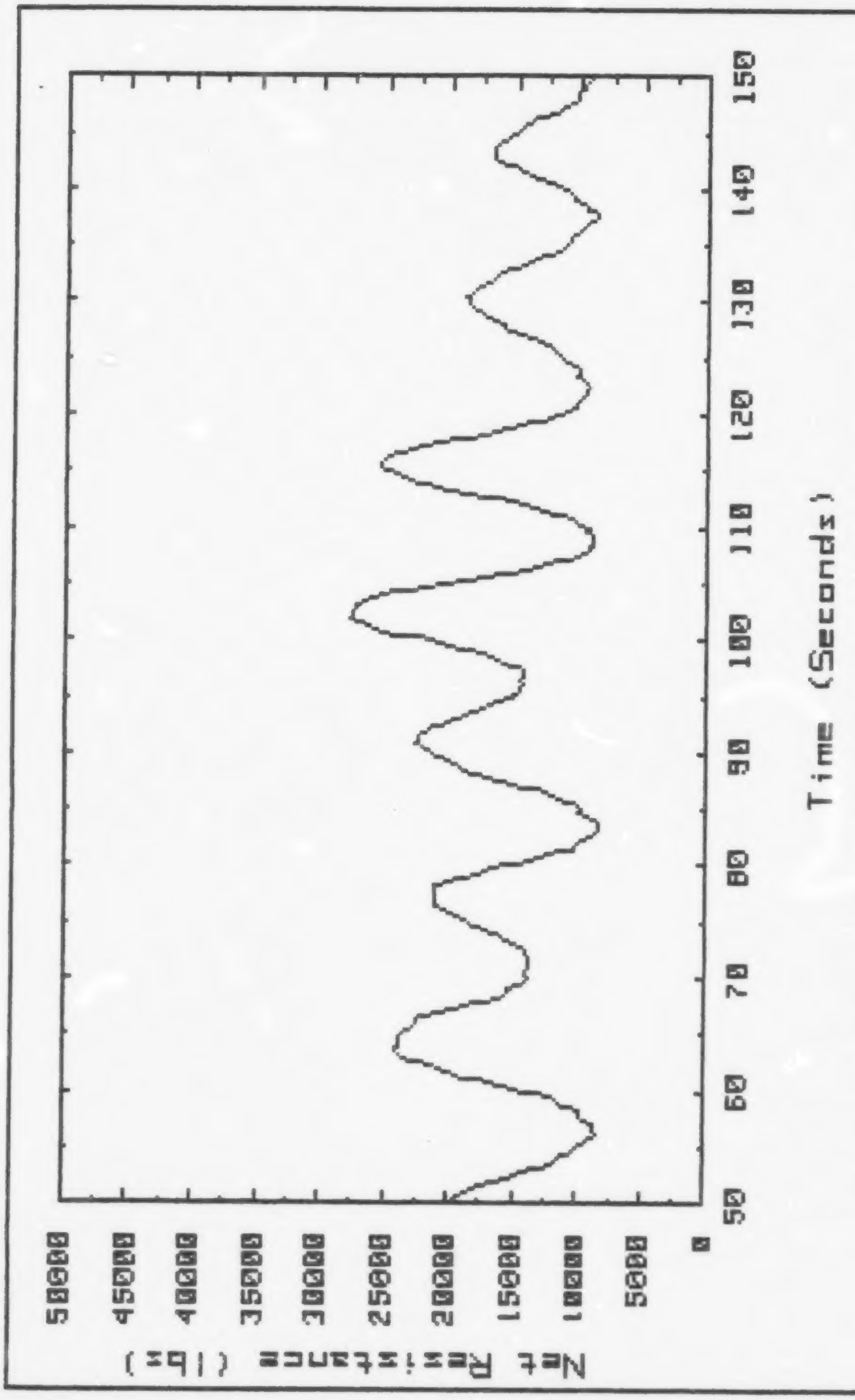
FULL-SCALE TOWED RESISTANCE TEST
TOW 9



FULL-SCALE TOWED RESISTANCE TEST
TOW 9A

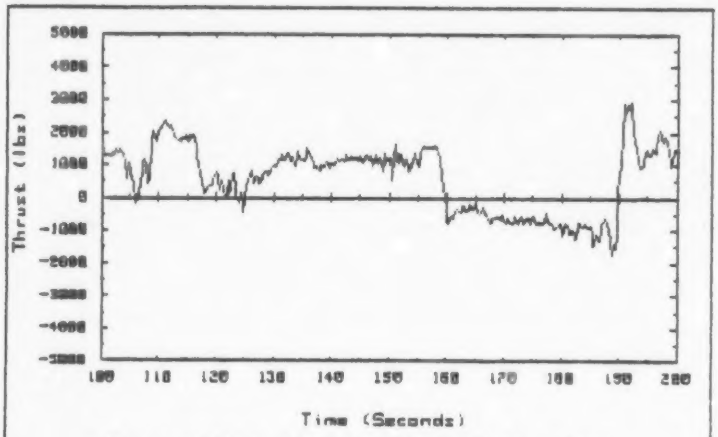


FULL-SCALE TOWED RESISTANCE TEST
TOW 9A

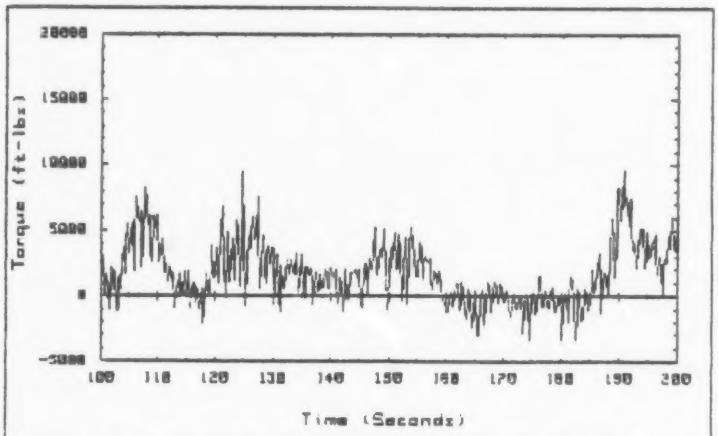


FULL-SCALE TOWED RESISTANCE TEST
TOW 9

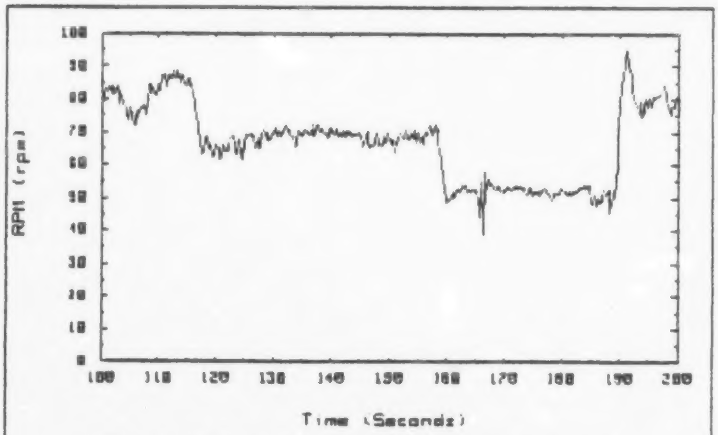
```
Test Results for Test TOW_10:  02/23/86, 12:28:53
             For the Interval Between  100  sec and  200  sec

   CHANNEL                               MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                          2939.7     -1742.7       597.1       1008.4
 2  Torque (ft-lbs)                       9636.8     -3387.1      1771.0       2321.2
 3  RPM (rpm)                               94.9        38.8        66.9         11.7
 4  Ship Speed (kts)                         5.8         4.0         4.9           .4
 5  Tow-Line Tension (lbs)               33013.0     14218.0     24611.4       4631.4
 6  Net Resistance (lbs)                 35042.2     14367.2     25208.5       4643.9

              Test Results for Test TOW_10:  02/23/86, 12:28:53
              For the Interval Between  100  sec and  200  sec

             Average Ship Speed                   4.9   kts
             Average Thrust                     597.1   lbs
             Average Torque                    1771.0   ft-lbs
             Average RPM                         66.9   RPM
             Average Tow-Line Tension         24611.4   lbs
             Average Net Resistance           25208.5   lbs
```



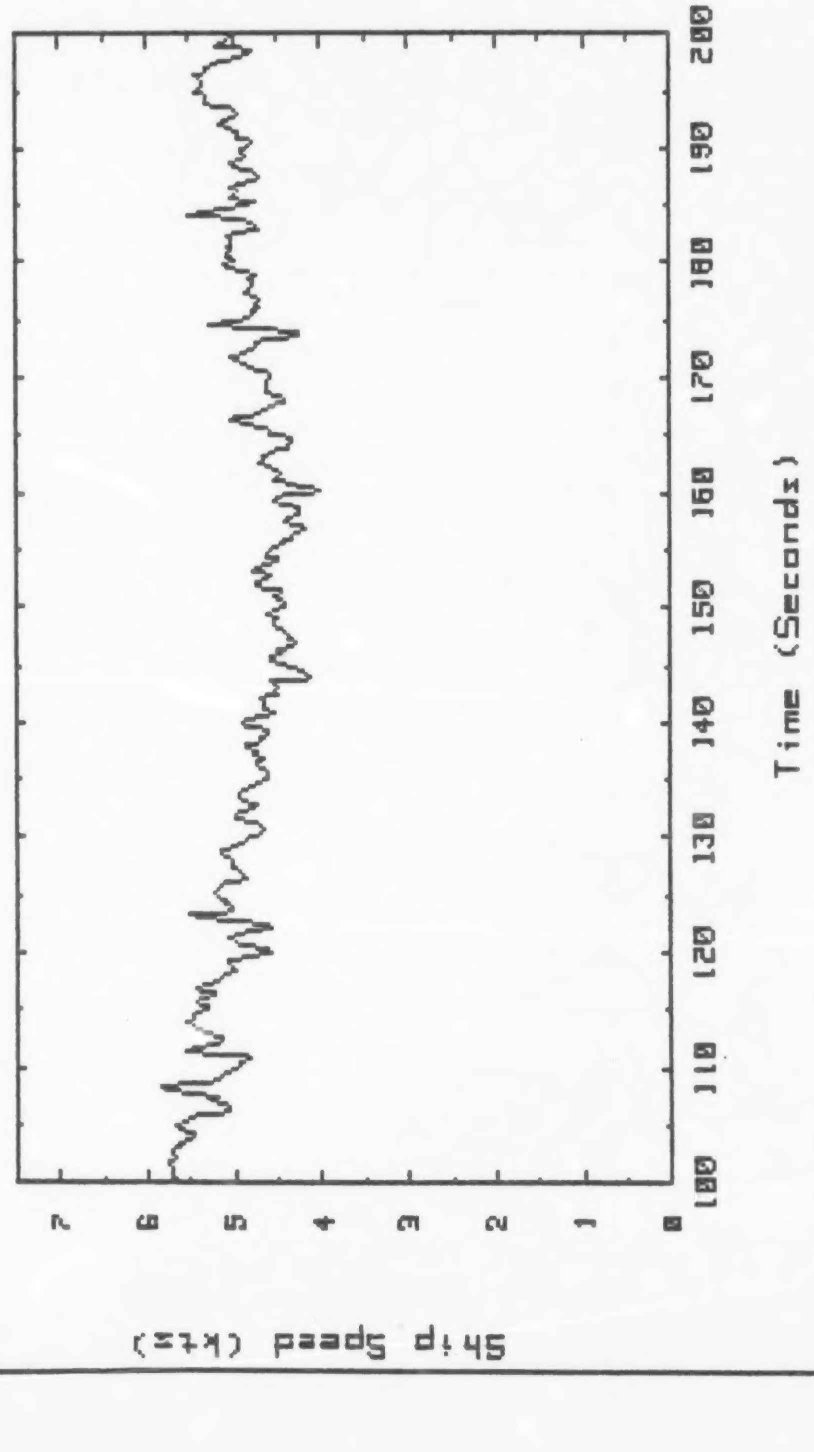
FULL-SCALE TOWED RESISTANCE TEST
TOW 10



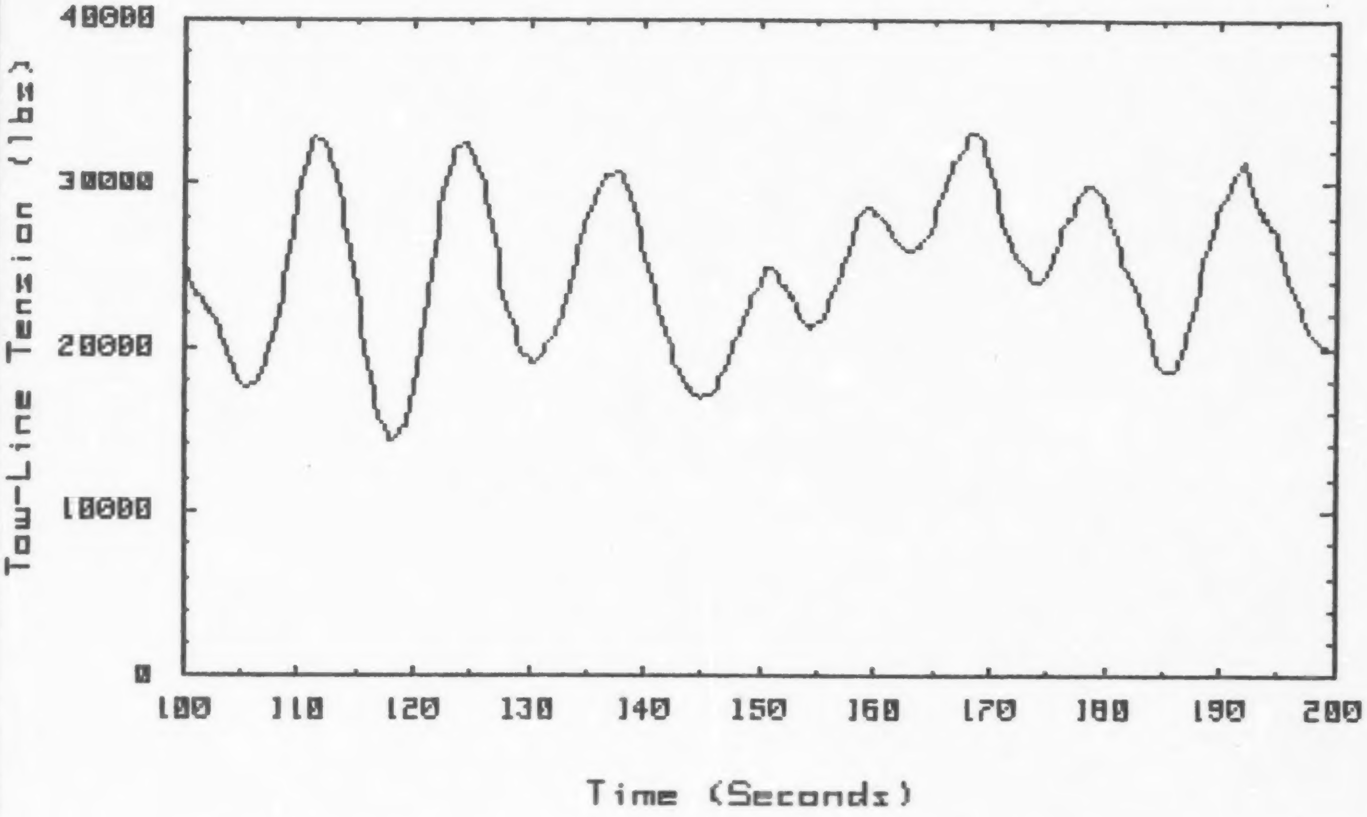
FULL-SCALE TOWED RESISTANCE TEST
TOW 10



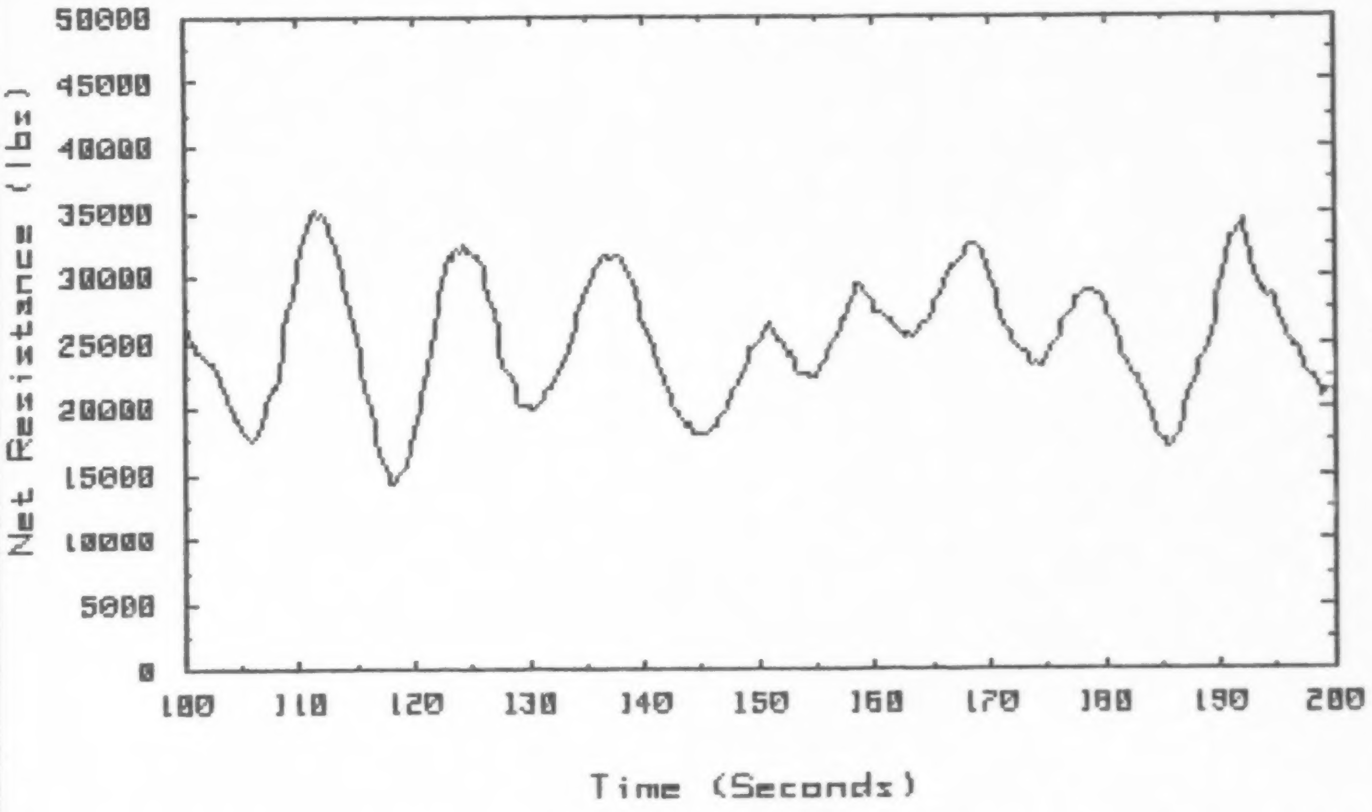
FULL-SCALE TOWED RESISTANCE TEST
TOW 10



FULL-SCALE TOWED RESISTANCE TEST
TOW 10

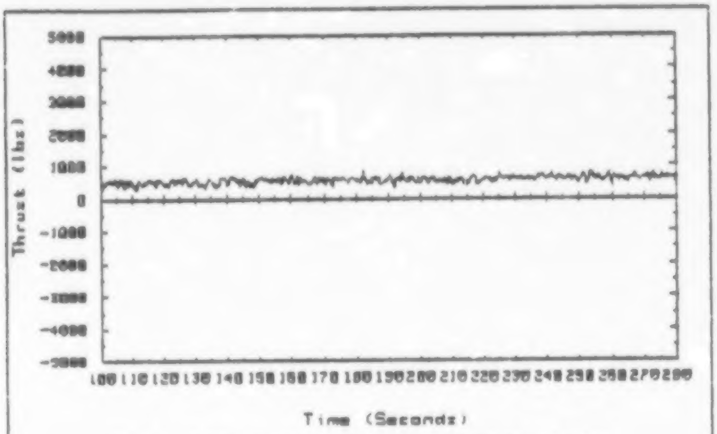


FULL-SCALE TOWED RESISTANCE TEST
TOW 10

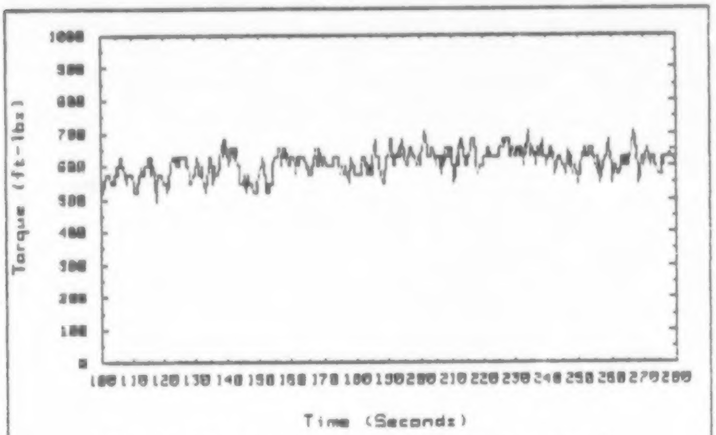


FULL-SCALE TOWED RESISTANCE TEST
TOW 10

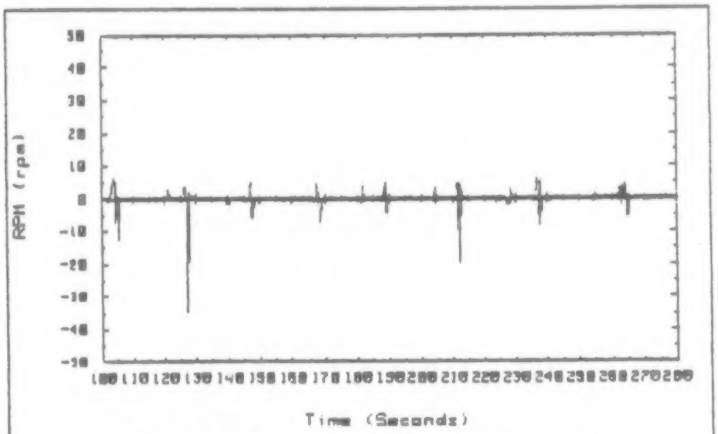
```
Test Results for Test TOW_12:  02/24/86, 15:09:01
             For the Interval Between  100  sec and  280  sec

   CHANNEL                             MAXIMUM    MINIMUM      MEAN     STDRD DEV

 1  Thrust (lbs)                         841.3      273.8      555.5        92.0
 2  Torque (ft-lbs)                      707.5      493.5      609.3        37.9
 3  RPM (rpm)                              6.1      -34.5         .1         2.0
 4  Ship Speed (kts)                       1.7         .9        1.2          .2
 5  Tow-Line Tension (lbs)             18353.3     4784.8    10673.2      2515.5
 6  Net Resistance (lbs)               18910.9     5300.9    11228.7      2521.4

             Test Results for Test TOW_12:  02/24/86, 15:09:01
             For the Interval Between  100  sec and  280  sec

            Average Ship Speed                    1.2   kts
            Average Thrust                      555.5   lbs
            Average Torque                      609.3   ft-lbs
            Average RPM                            .1   RPM
            Average Tow-Line Tension          10673.2   lbs
            Average Net Resistance            11228.7   lbs
```



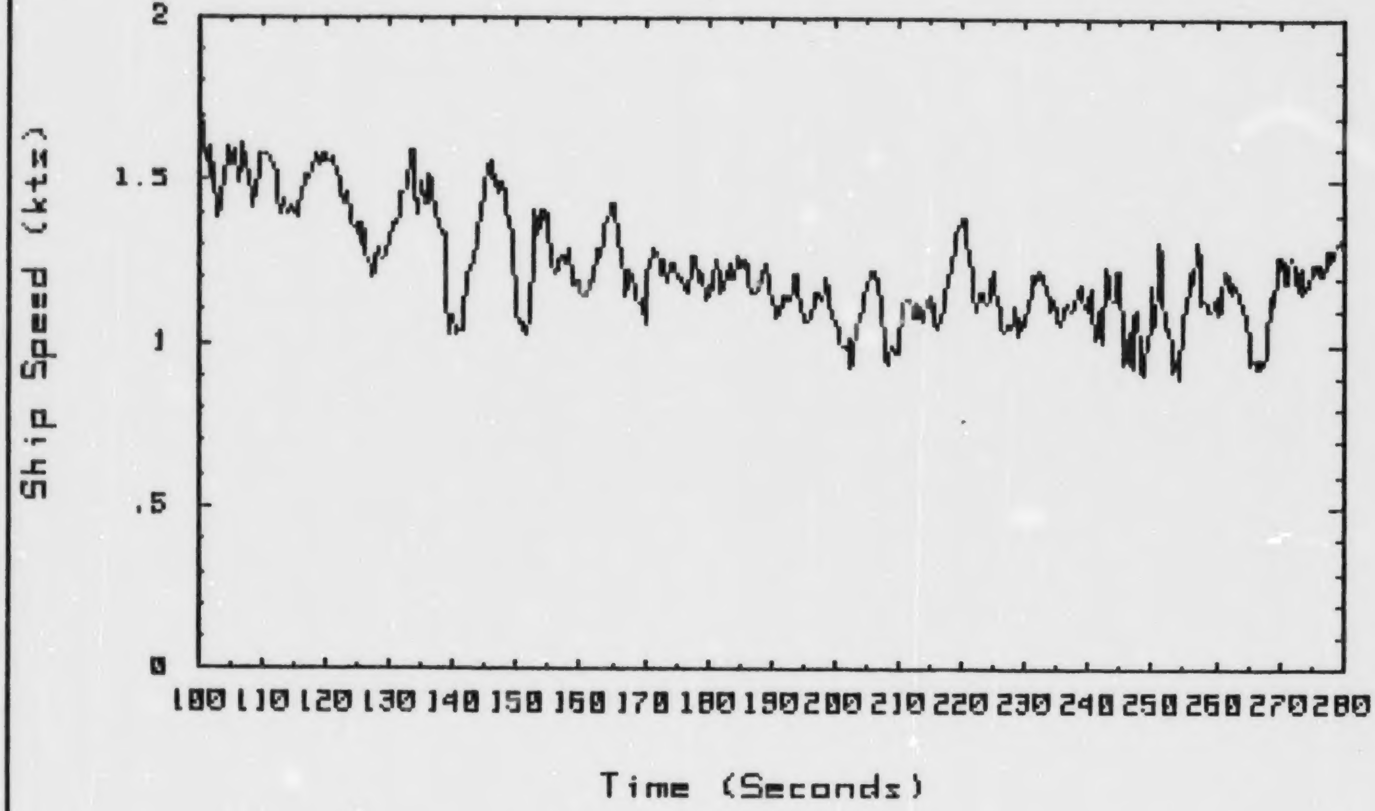
FULL-SCALE TOWED RESISTANCE TEST
TOW 12



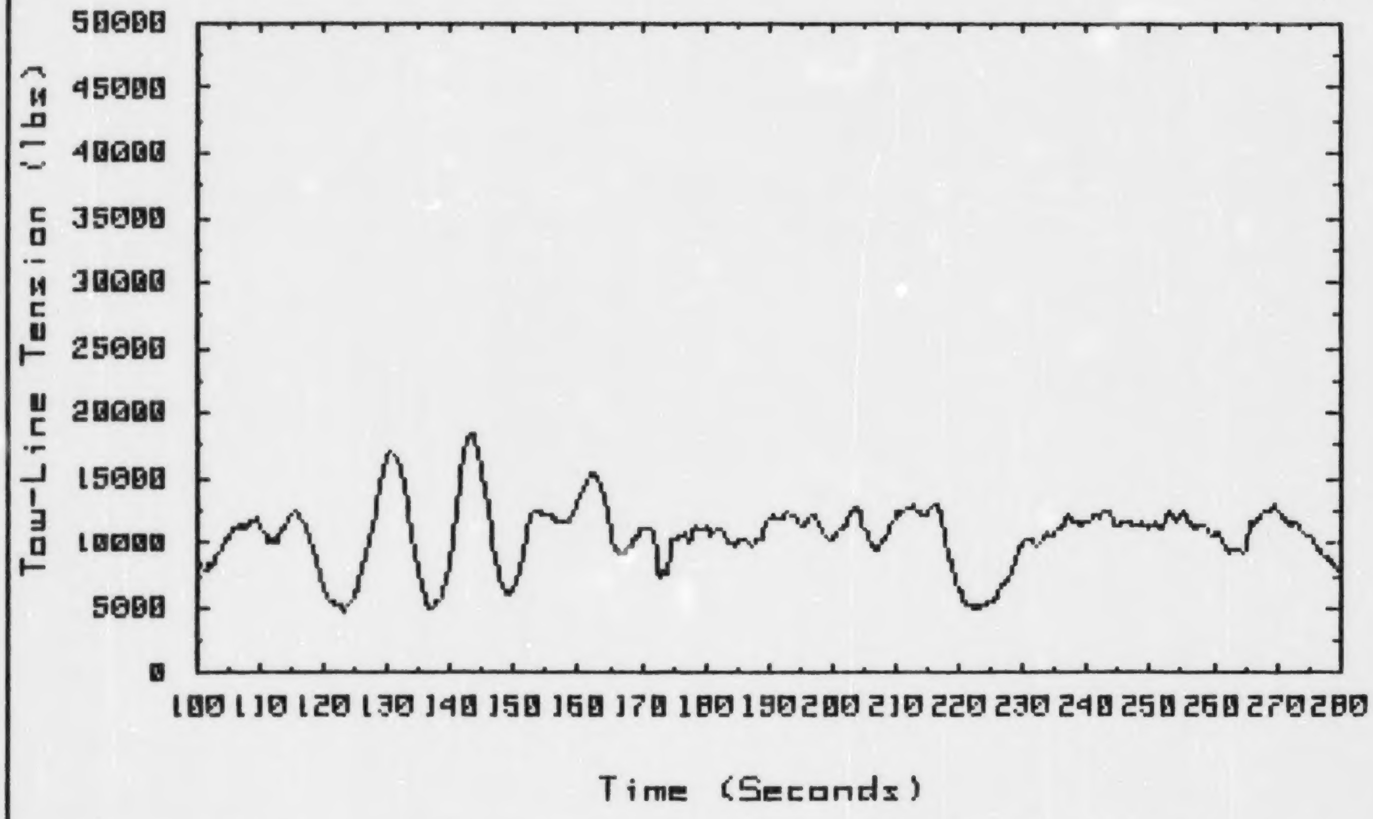
FULL-SCALE TOWED RESISTANCE TEST
TOW 12



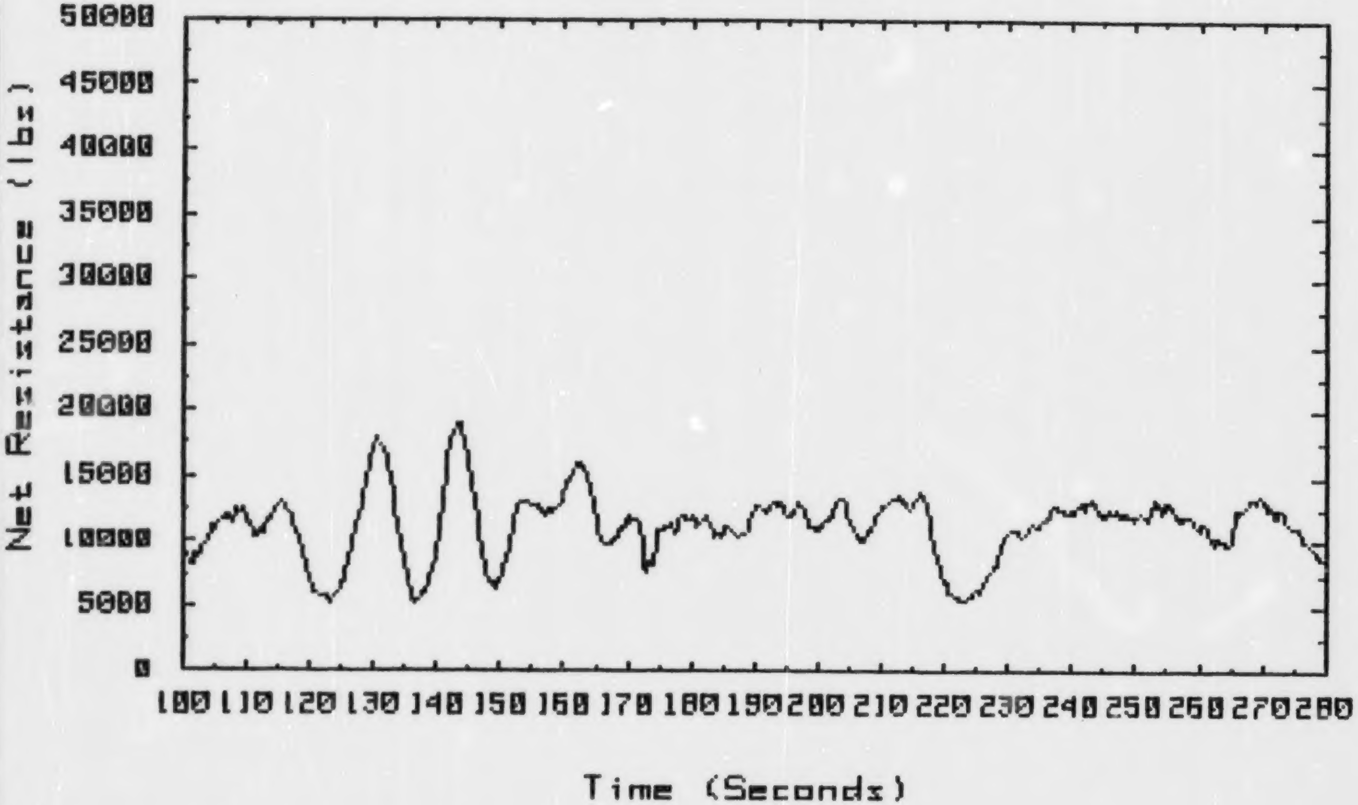
FULL-SCALE TOWED RESISTANCE TEST
TOW 12



FULL-SCALE TOWED RESISTANCE TEST
TOW 12

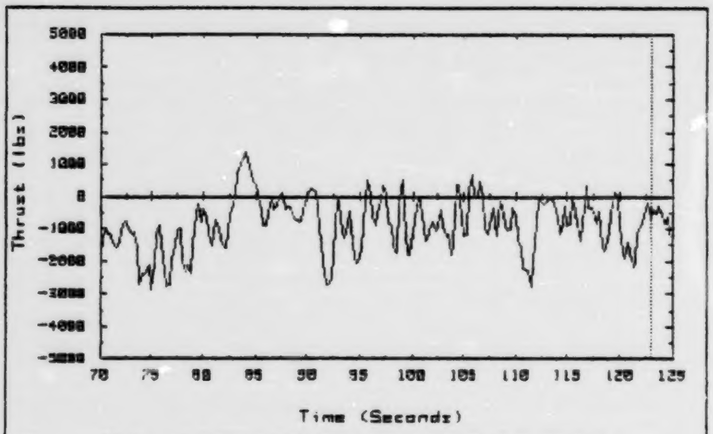


FULL-SCALE TOWED RESISTANCE TEST
TOW 12

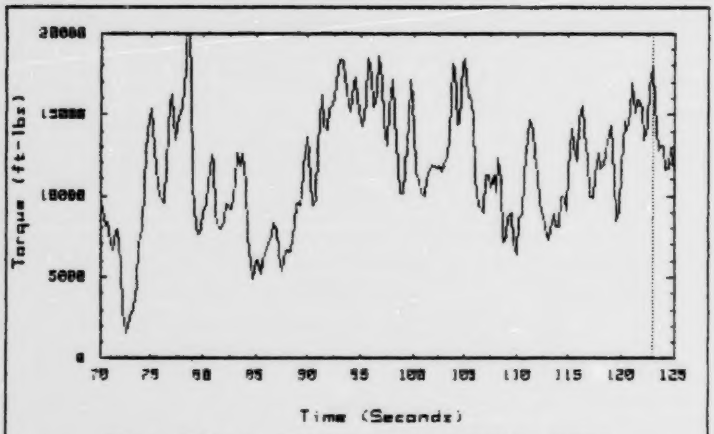


FULL-SCALE TOWED RESISTANCE TEST
TOW 12

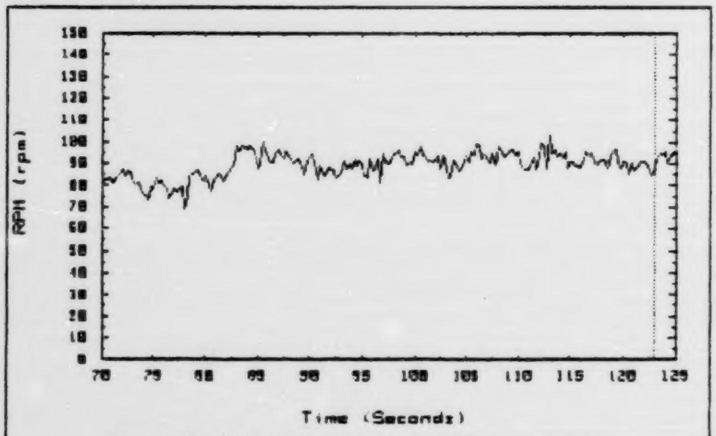
```
Test Results for Test TOW_13:  02/24/86, 17:34:00
              For the Interval Between  70  sec and  123  sec

   CHANNEL                               MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                          1377.9     -2878.8      -874.4       851.2
 2  Torque (ft-lbs)                      20765.2      1590.3     11561.9      3779.9
 3  RPM (rpm)                              102.9        68.7        89.3         5.9
 4  Ship Speed (kts)                         8.8         6.6         7.6          .4
 5  Tow-Line Tension (lbs)               51841.9     29629.7     38241.3      6083.3
 6  Net Resistance (lbs)                 52841.5     27454.4     37366.9      6334.7

              Test Results for Test TOW_13:  02/24/86, 17:34:00
              For the Interval Between  70  sec and  123  sec

             Average Ship Speed                7.6   kts
             Average Thrust                 -874.4   lbs
             Average Torque                11561.9   ft-lbs
             Average RPM                      89.3   RPM
             Average Tow-Line Tension      38241.3   lbs
             Average Net Resistance        37366.9   lbs
```



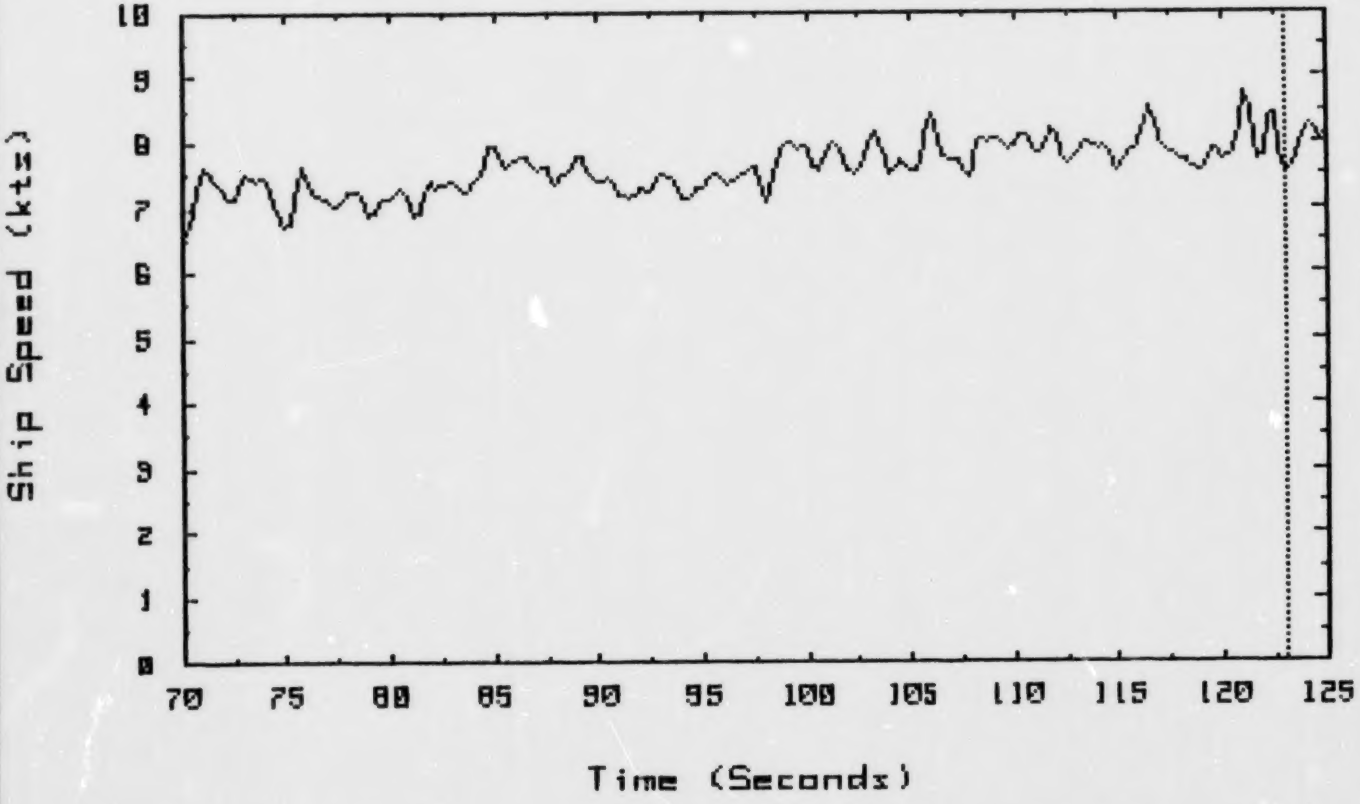
FULL-SCALE TOWED RESISTANCE TEST
TOW 13



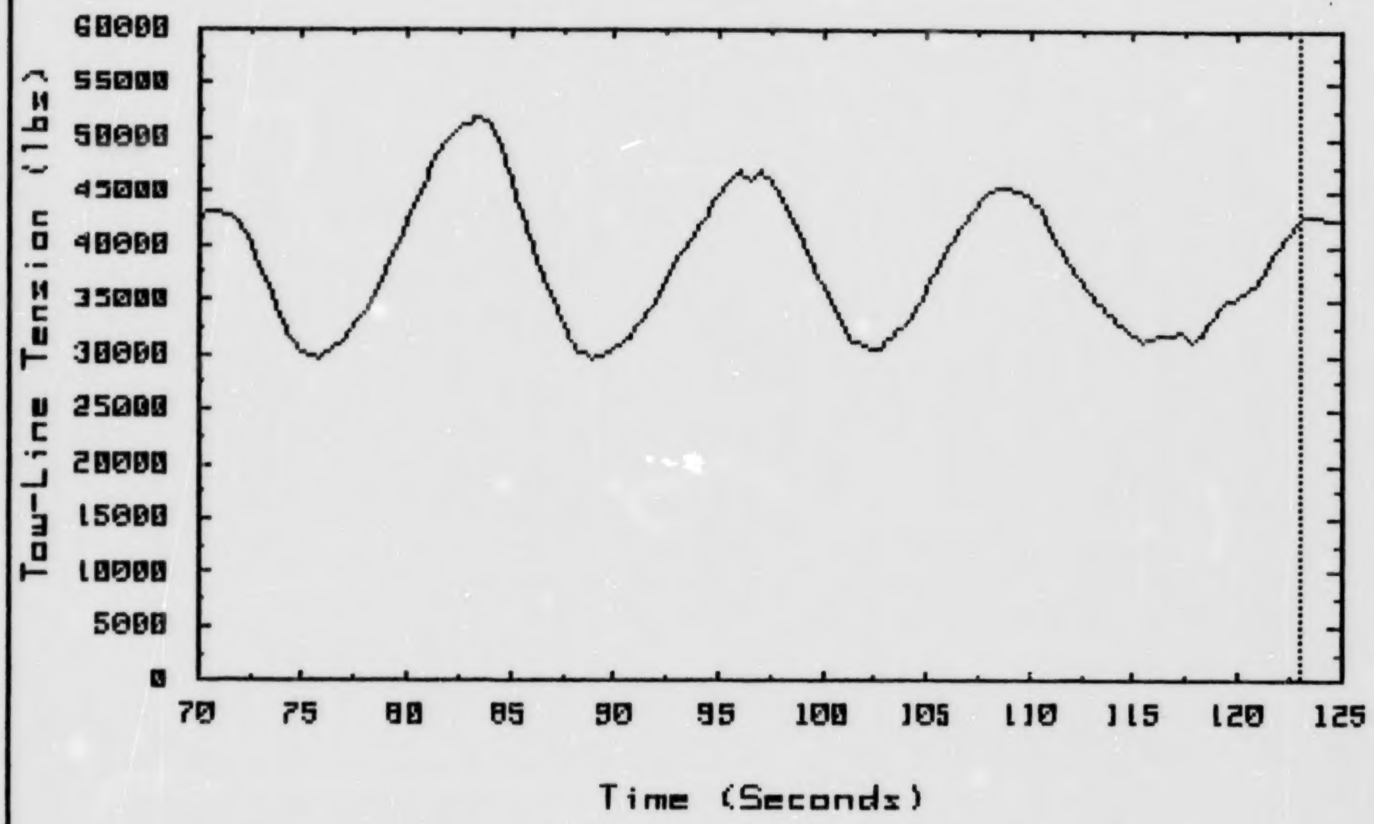
FULL-SCALE TOWED RESISTANCE TEST
TOW 13



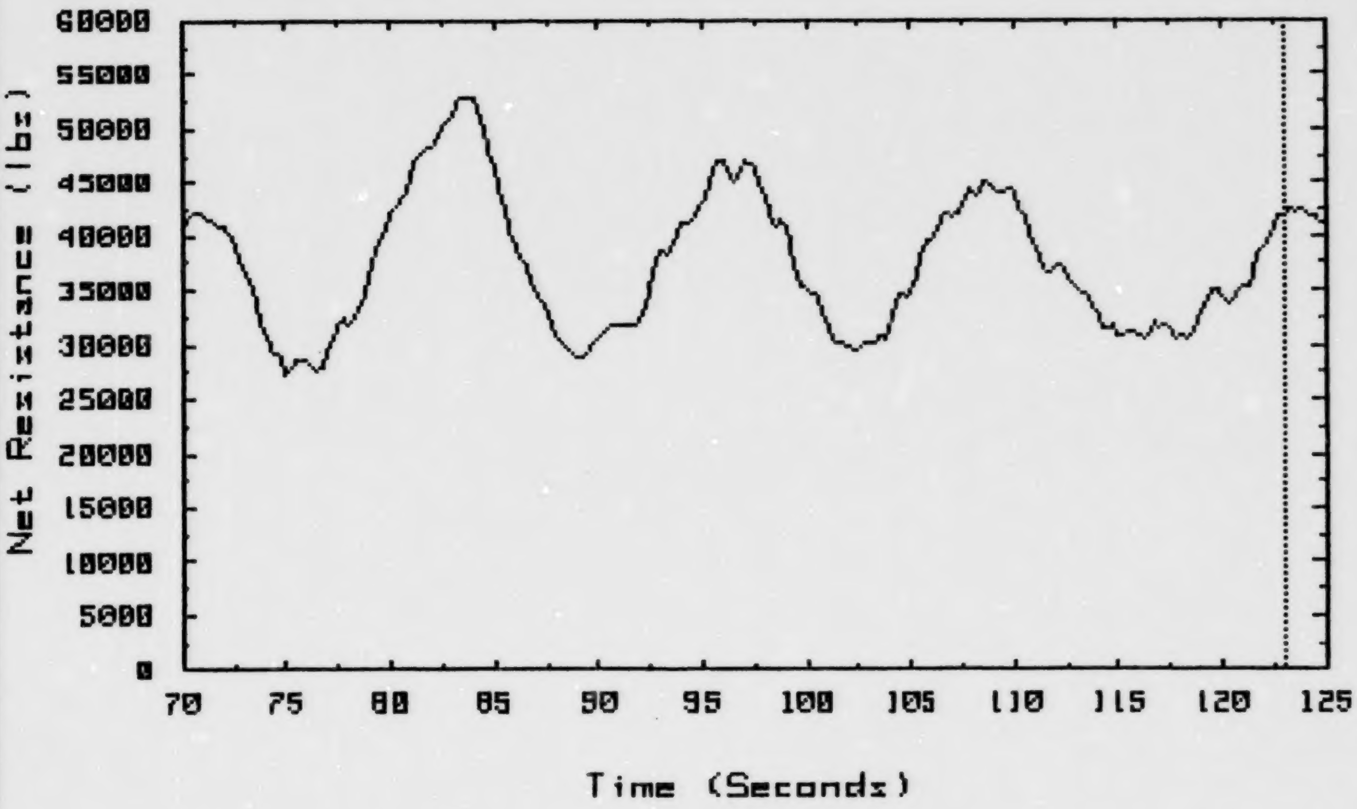
FULL-SCALE TOWED RESISTANCE TEST
TOW 13



FULL-SCALE TOWED RESISTANCE TEST
TOW 13

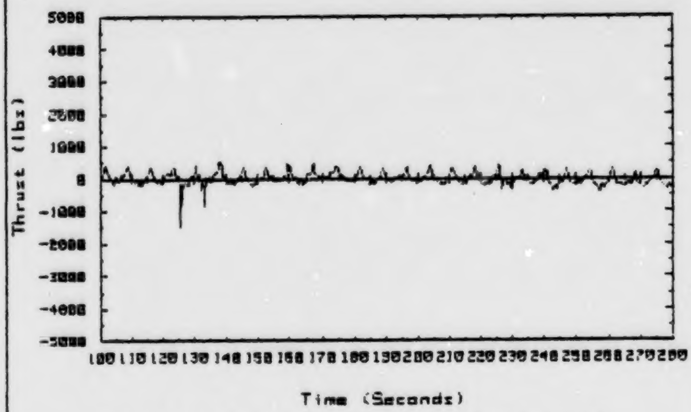


FULL-SCALE TOWED RESISTANCE TEST
TOW 13

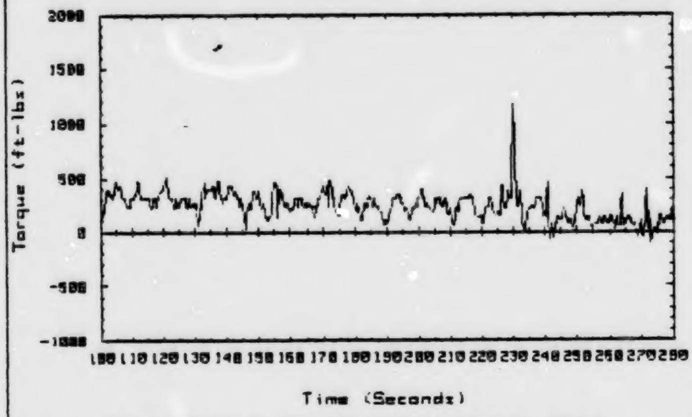


FULL-SCALE TOWED RESISTANCE TEST
TOW 13

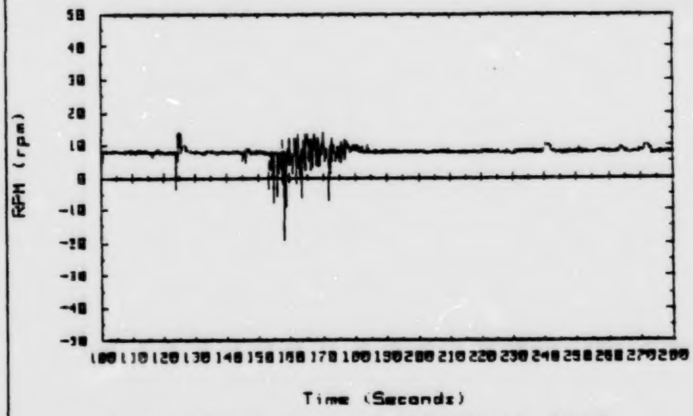
```
Test Results for Test TOW_14:  02/25/86, 08:49:52
              For the Interval Between  100  sec and  280  sec

   CHANNEL                               MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                           504.5     -1482.0         4.8        184.8
 2  Torque (ft-lbs)                       1177.8      -105.9       245.8        129.4
 3  RPM (rpm)                               13.8       -19.1         8.0          2.1
 4  Ship Speed (kts)                         2.5         1.8         2.1           .1
 5  Tow-Line Tension (lbs)               23003.7     11344.8     16713.4       2437.2
 6  Net Resistance (lbs)                 23082.6     11329.1     16718.2       2440.1

              Test Results for Test TOW_14:  02/25/86, 08:49:52
              For the Interval Between  100  sec and  280  sec

             Average Ship Speed                 2.1   kts
             Average Thrust                     4.8   lbs
             Average Torque                   245.8   ft-lbs
             Average RPM                        8.0   RPM
             Average Tow-Line Tension       16713.4   lbs
             Average Net Resistance         16718.2   lbs
```



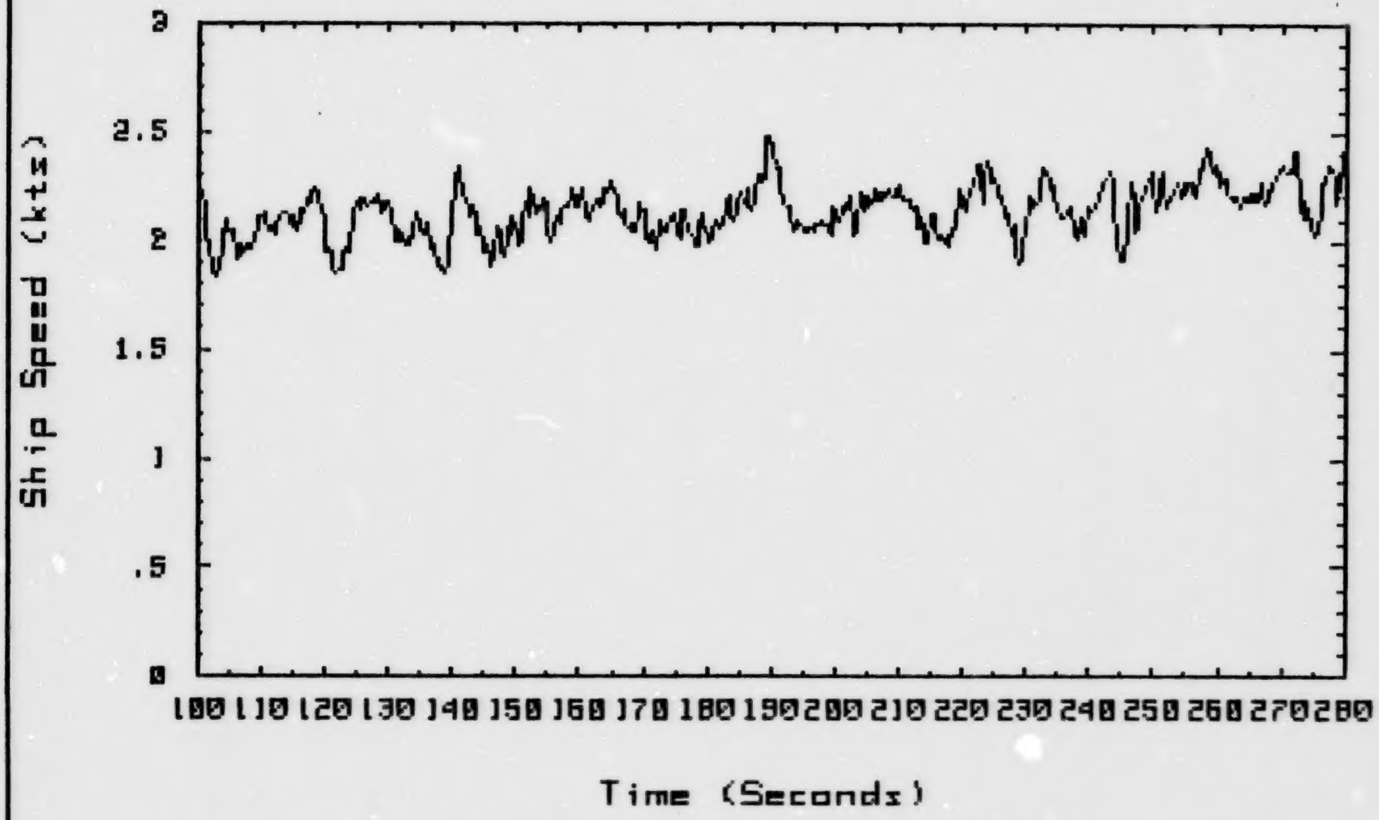
FULL-SCALE TOWED RESISTANCE TEST
TOW 14



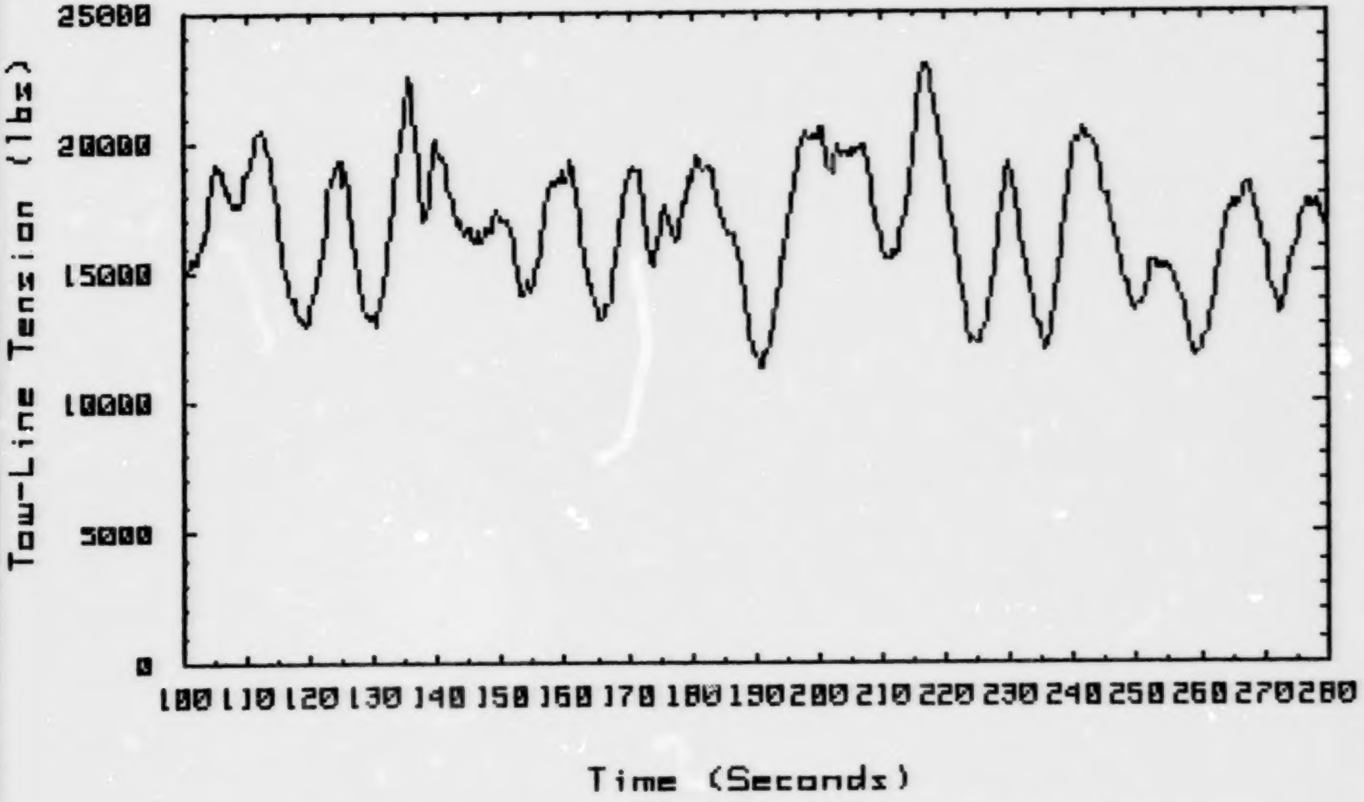
FULL-SCALE TOWED RESISTANCE TEST
TOW 14



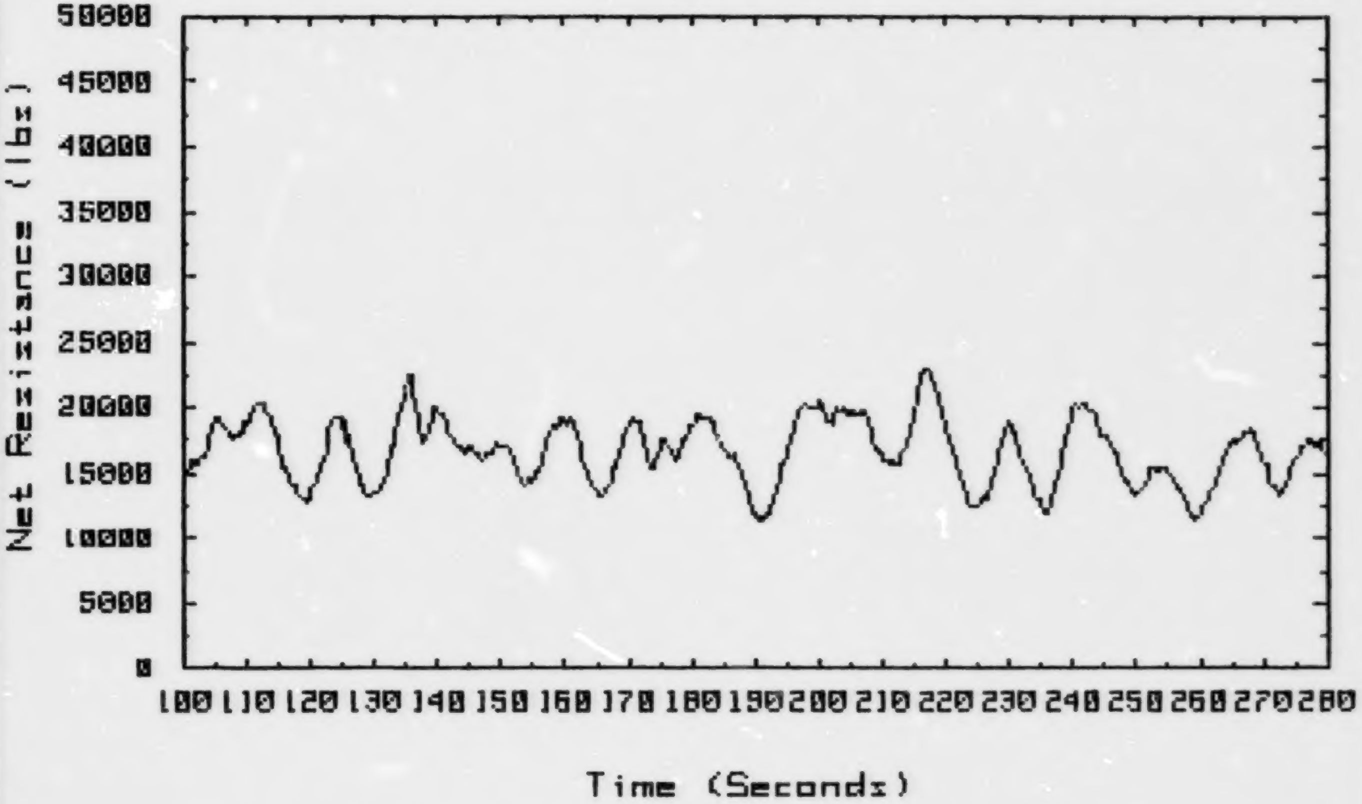
FULL-SCALE TOWED RESISTANCE TEST
TOW 14



FULL-SCALE TOWED RESISTANCE TEST
TOW 14

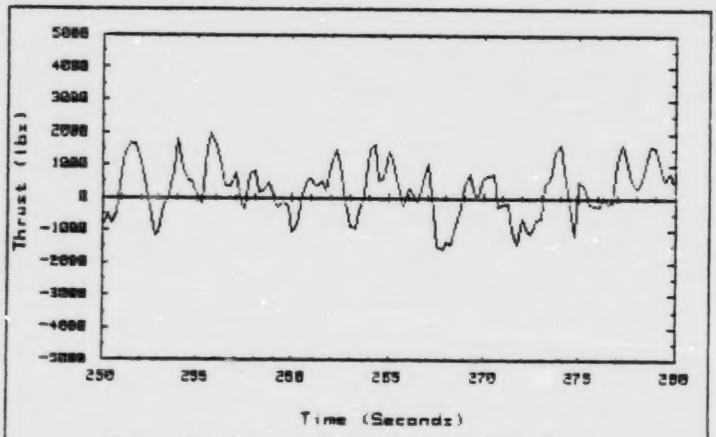


FULL-SCALE TOWED RESISTANCE TEST
TOW 14

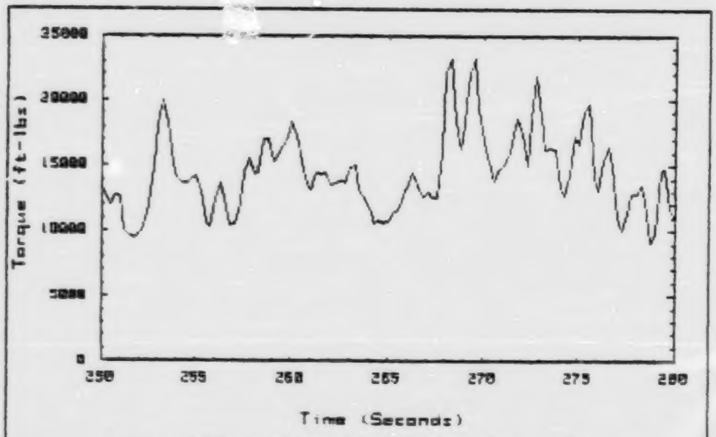


FULL-SCALE TOWED RESISTANCE TEST
TOW 14

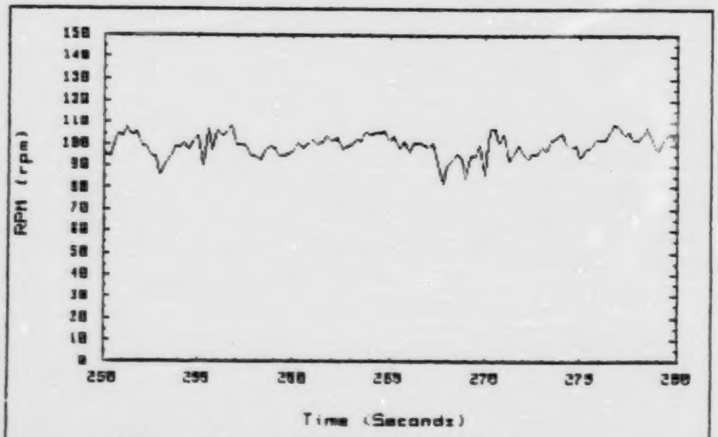
```
Test Results for Test TOW_15:  02/25/86, 09:53:17
            For the Interval Between  250  sec and  280  sec

   CHANNEL                              MAXIMUM      MINIMUM       MEAN       STDRD DEV

 1  Thrust (lbs)                         1959.3      -1588.1       245.2        828.6
 2  Torque (ft-lbs)                     23270.6       9043.2     14440.7       3020.2
 3  RPM (rpm)                             109.9         81.9        99.5          5.2
 4  Ship Speed (kts)                        9.1          6.7         7.4           .4
 5  Tow-Line Tension (lbs)              43988.9      30922.9     37608.7       2733.7
 6  Net Resistance (lbs)                43772.5      31274.1     37854.0       2779.7

             Test Results for Test TOW_15:  02/25/86, 09:53:17
             For the Interval Between  250  sec and  280  sec

            Average Ship Speed .                7.4   kts
            Average Thrust                    245.2   lbs
            Average Torque                  14440.7   ft-lbs
            Average RPM                        99.5   RPM
            Average Tow-Line Tension        37608.7   lbs
            Average Net Resistance          37854.0   lbs
```



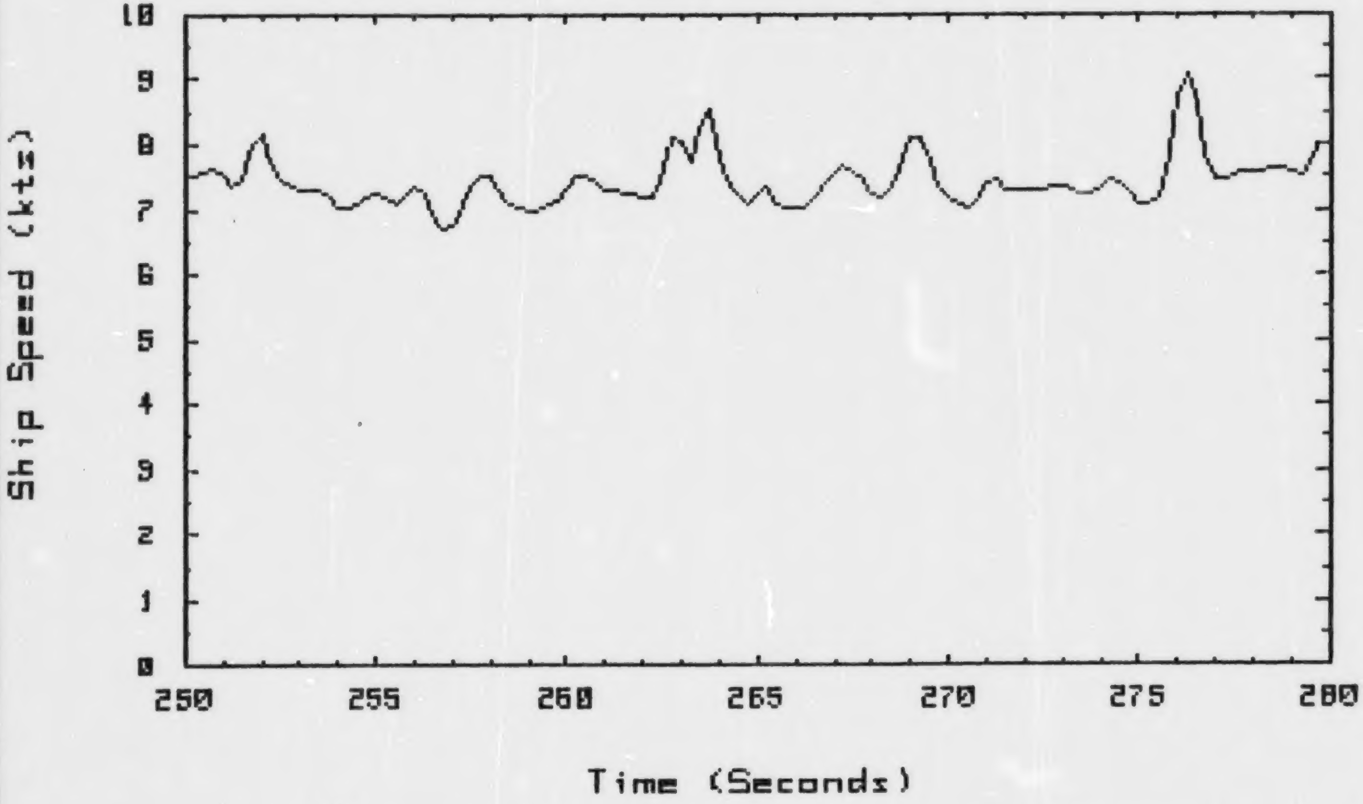
FULL-SCALE TOWED RESISTANCE TEST
TOW 15



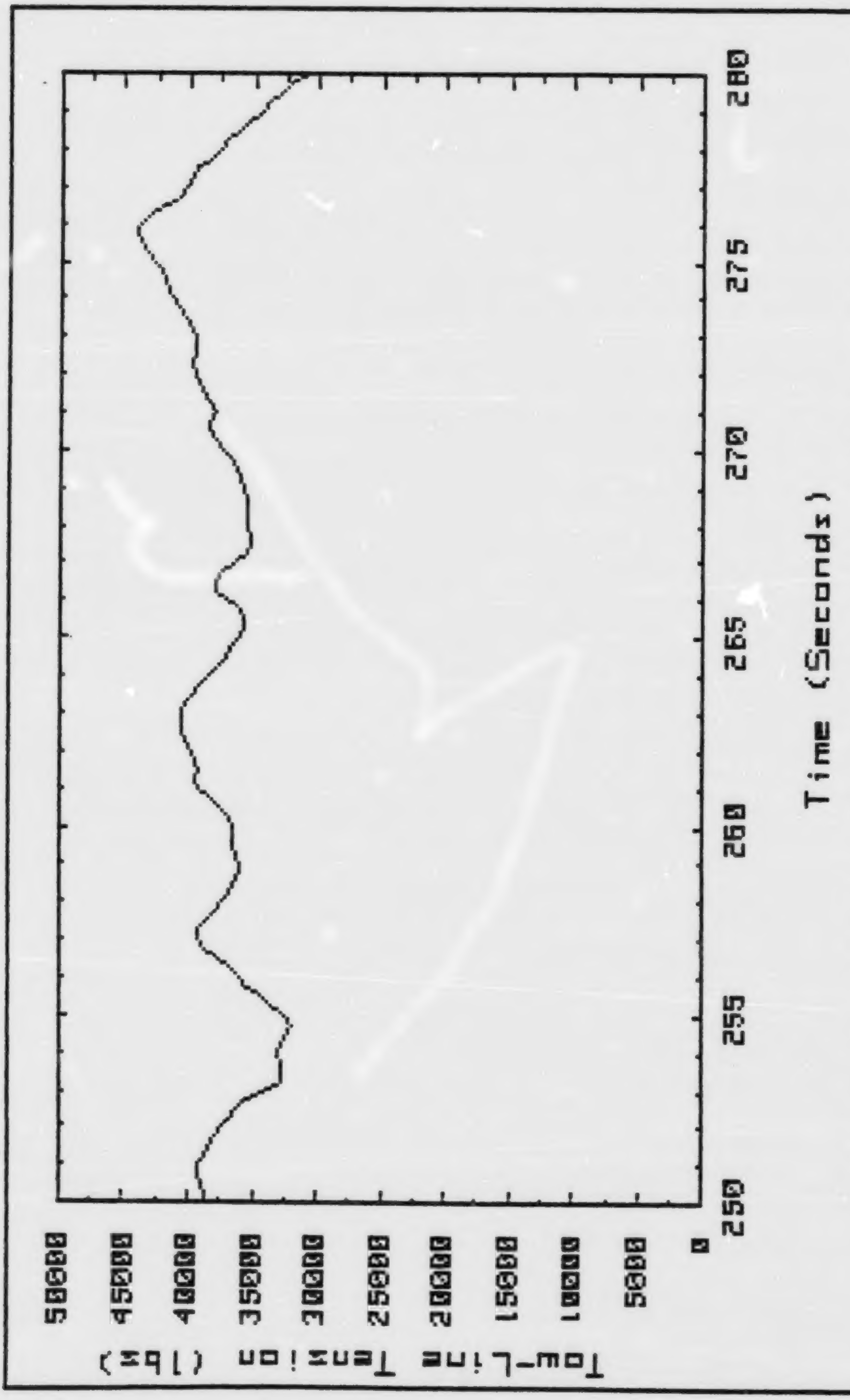
FULL-SCALE TOWED RESISTANCE TEST
TOW 15



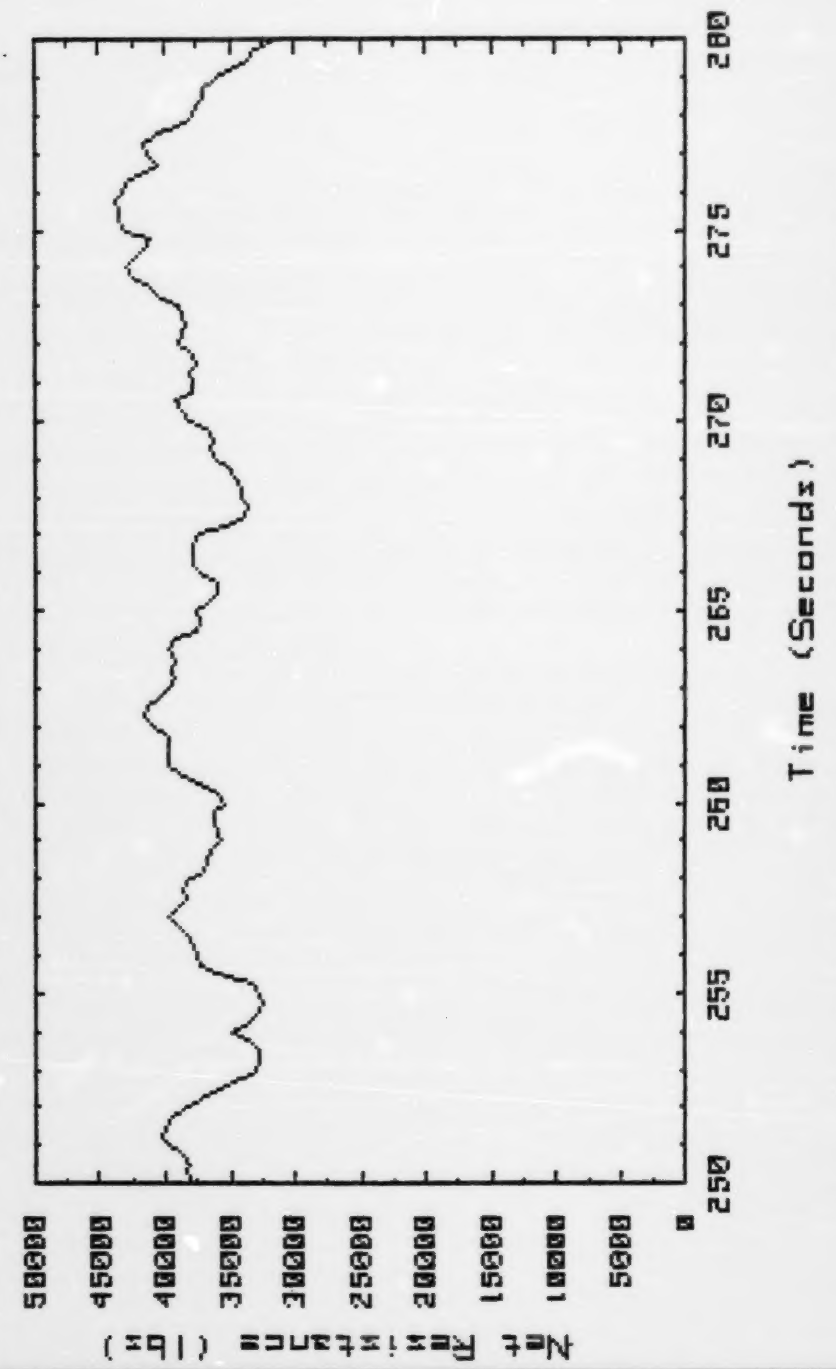
FULL-SCALE TOWED RESISTANCE TEST
TOW 15



FULL-SCALE TOWED RESISTANCE TEST
TOW 15

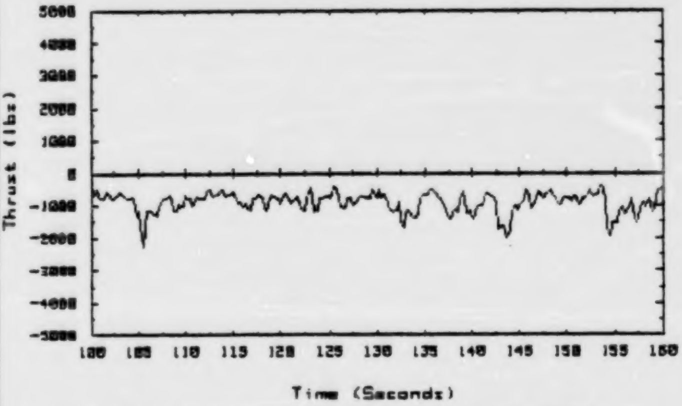


FULL-SCALE TOWED RESISTANCE TEST
TOW 15

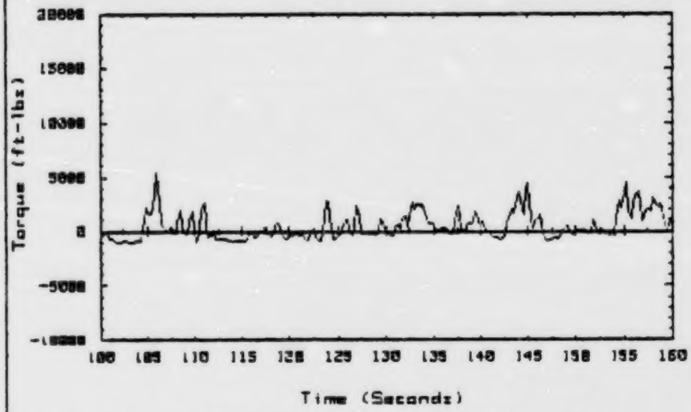


FULL-SCALE TOWED RESISTANCE TEST
TOW 15

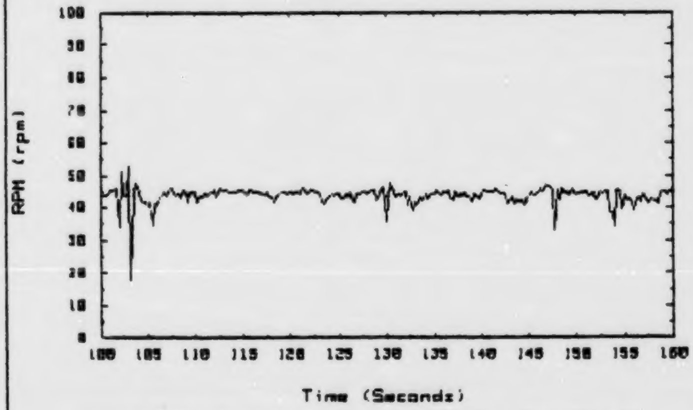
```
Test Results for Test TOW_16:  02/25/86, 11:10:58
            For the Interval Between  100  sec and  160  sec

  CHANNEL                             MAXIMUM     MINIMUM      MEAN     STDRD DEV

 1  Thrust (lbs)                      -370.3     -2309.5     -902.2       323.8
 2  Torque (ft-lbs)                   5433.4     -1091.9      476.5      1265.4
 3  RPM (rpm)                           52.9        17.7       43.8         2.8
 4  Ship Speed (kts)                     4.8         3.7        4.4          .2
 5  Tow-Line Tension (lbs)           26105.1     18265.5    22117.3      1874.7
 6  Net Resistance (lbs)             25539.7     17611.4    21215.1      1876.6

            Test Results for Test TOW_16:  02/25/86, 11:10:58
            For the Interval Between  100  sec and  160  sec

           Average Ship Speed                    4.4   kts
           Average Thrust                     -902.2   lbs
           Average Torque                      476.5   ft-lbs
           Average RPM                          43.8   RPM
           Average Tow-Line Tension          22117.3   lbs
           Average Net Resistance            21215.1   lbs
```



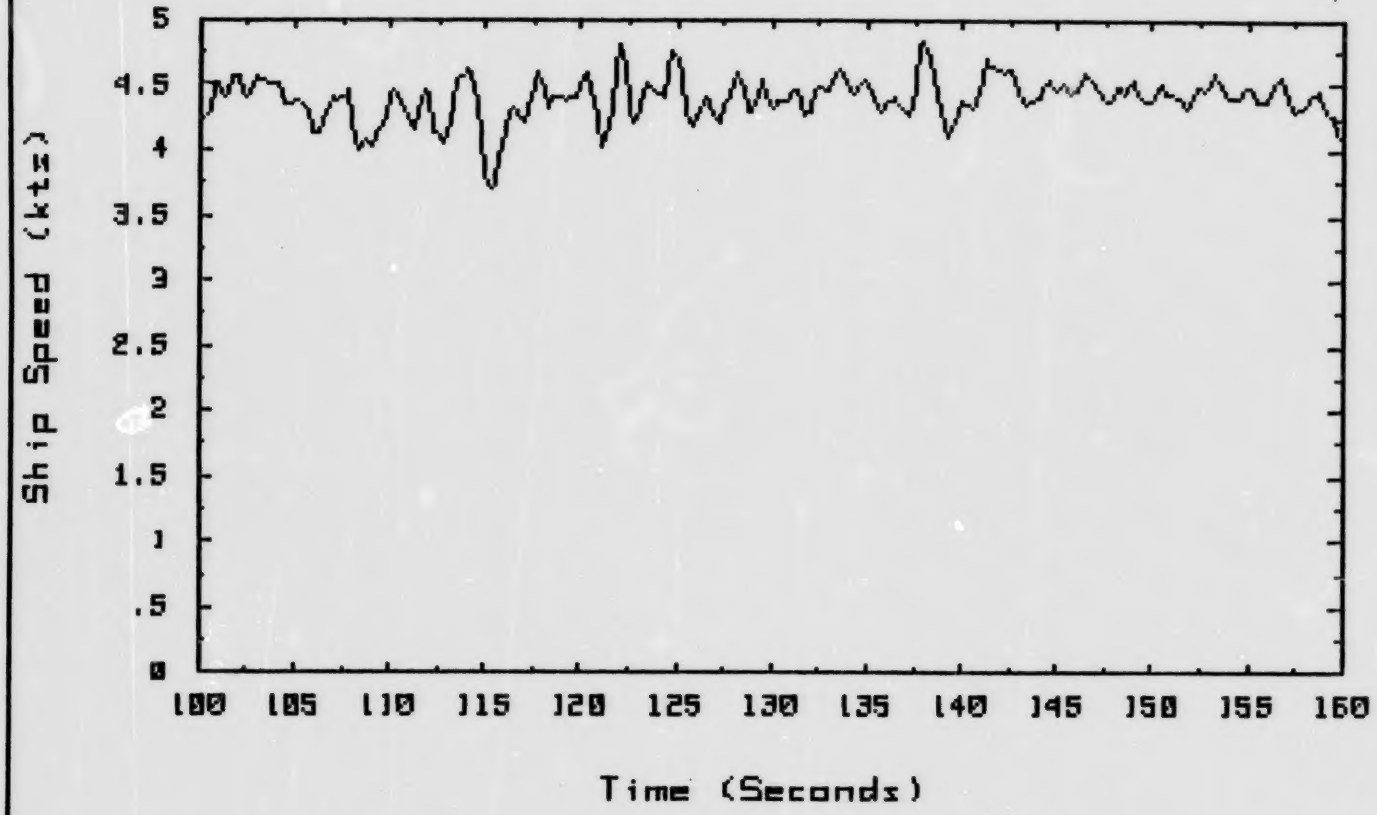
FULL-SCALE TOWED RESISTANCE TEST
TOW 16



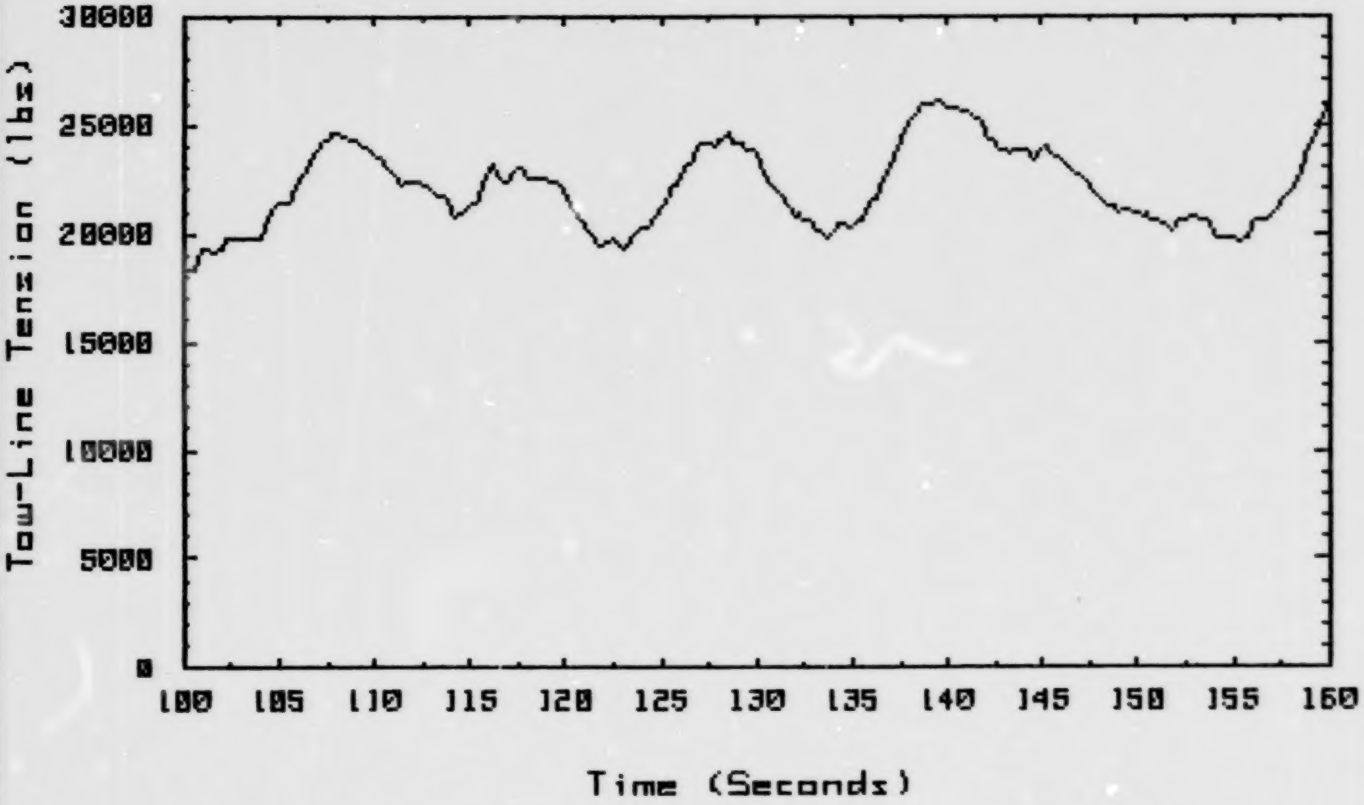
FULL-SCALE TOWED RESISTANCE TEST
TOW 16



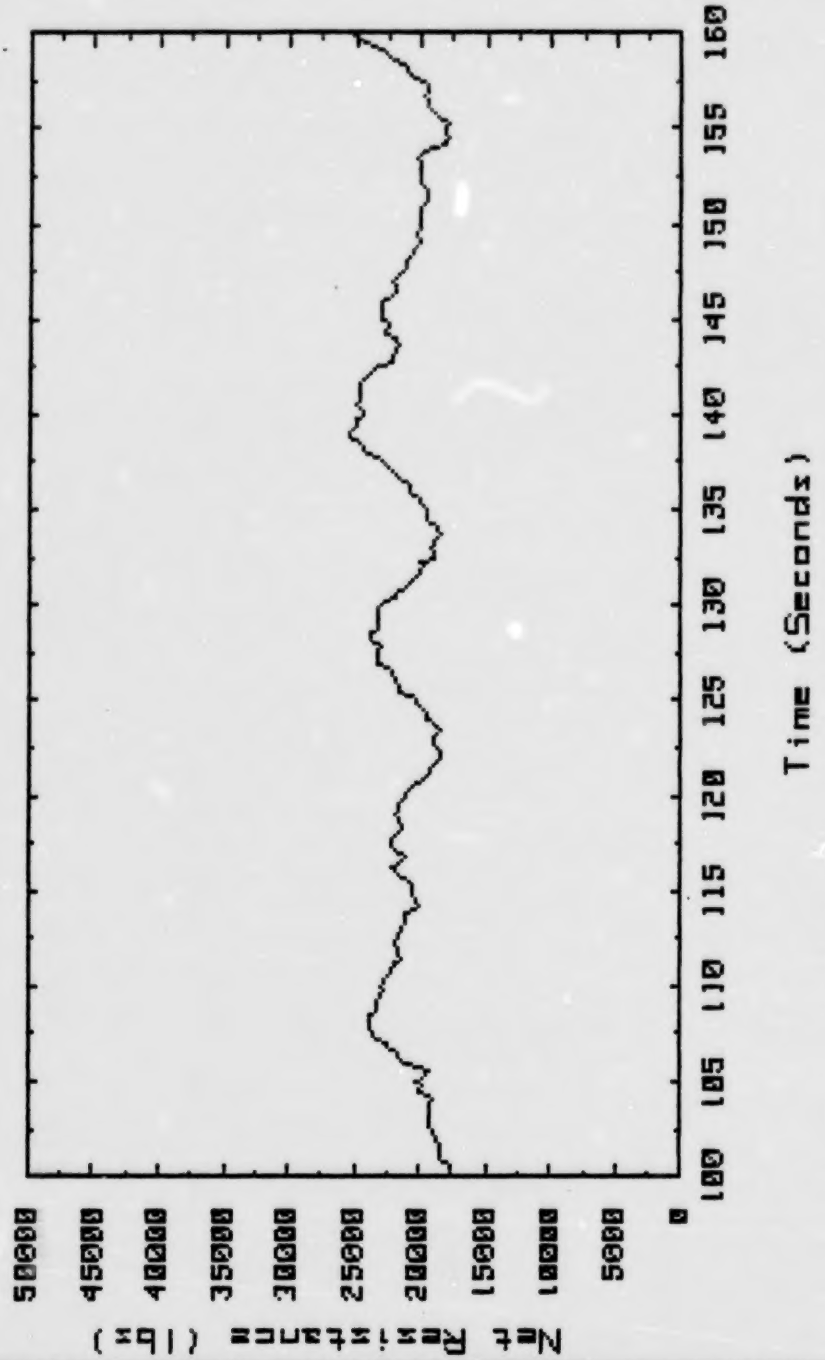
FULL-SCALE TOWED RESISTANCE TEST
TOW 16



FULL-SCALE TOWED RESISTANCE TEST
TOW 16



FULL-SCALE TOWED RESISTANCE TEST
TOW 16

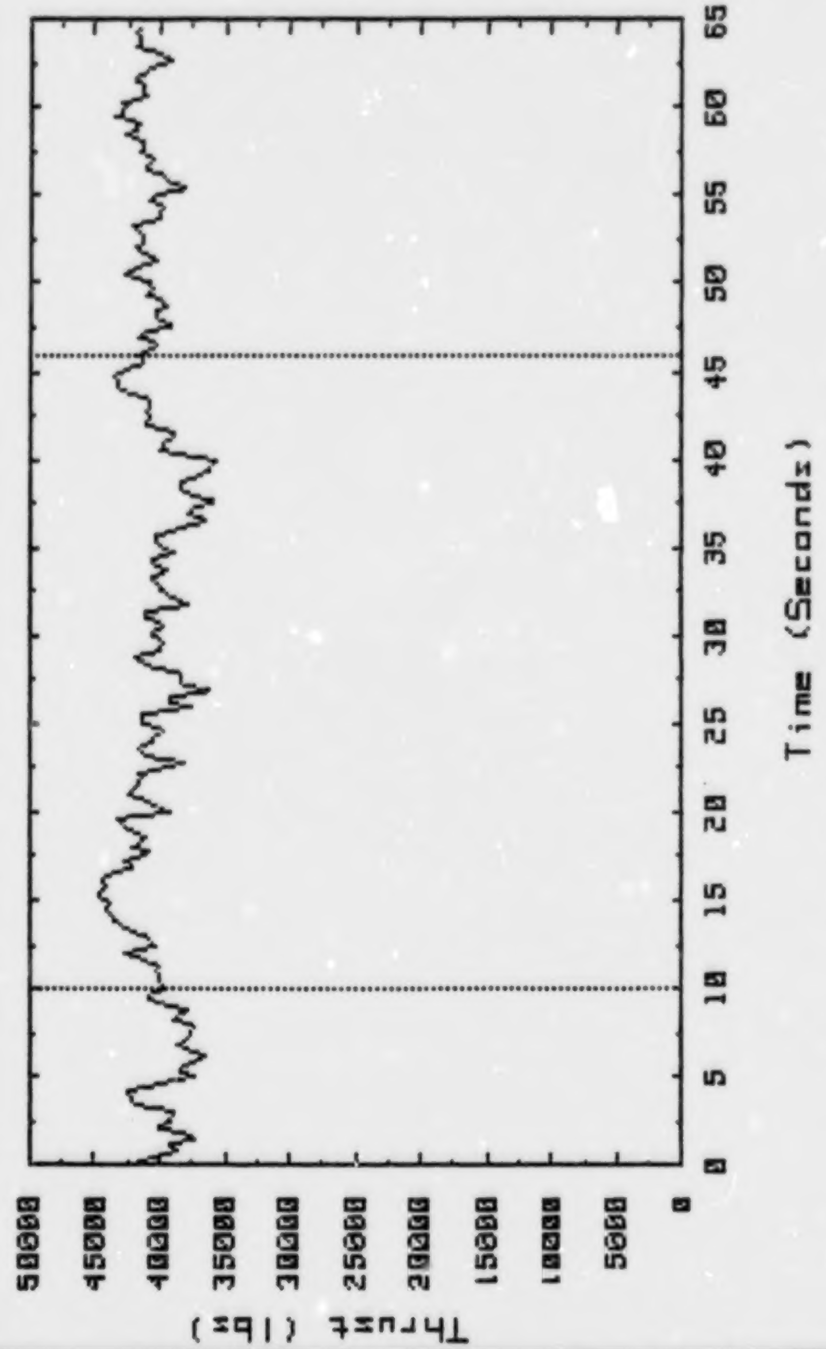


FULL-SCALE TOWED RESISTANCE TEST
TOW 16

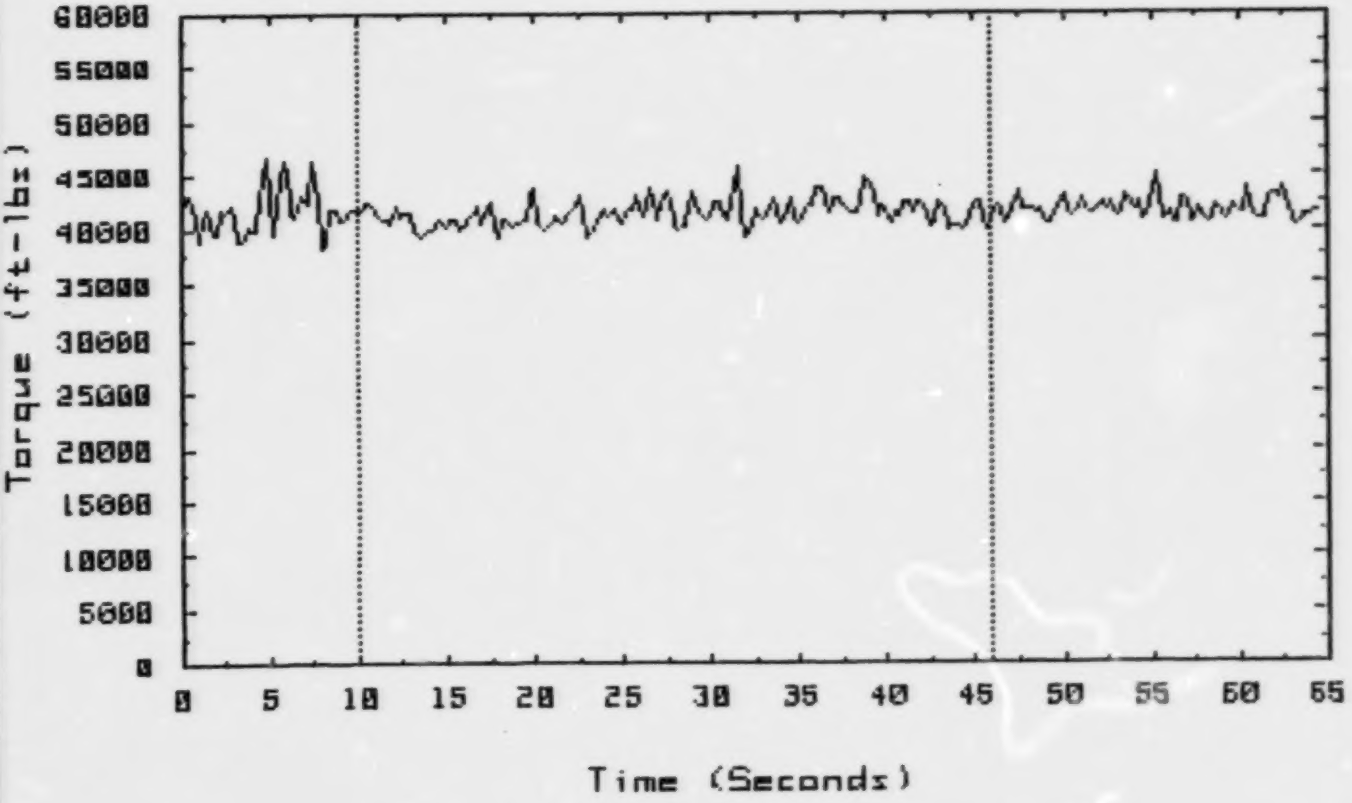
APPENDIX D

SELF-PROPELLED TEST RESULTS AND ANALYSIS

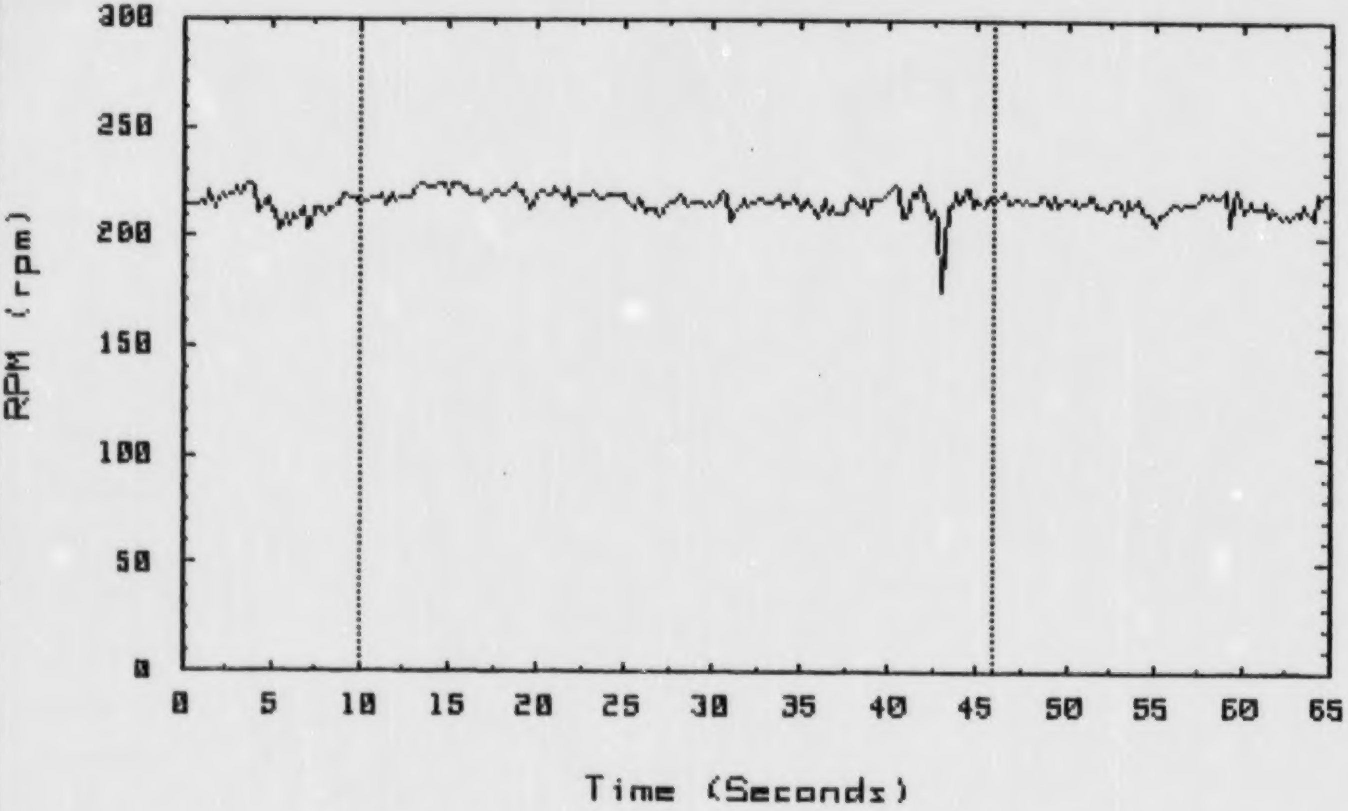
```
                 Test Results for Test SP_1:  02/21/86, 18:39:18
                 For the Interval Between  10  sec and  46  sec

   CHANNEL                              MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                        44663.8     35712.4    40496.6       2015.2
 2  Torque (ft-lbs)                     45762.5     39190.9    41513.5       1183.7
 3  RPM (rpm)                             224.1       174.5      216.9          5.2
 4  Ship Speed (kts)                        3.6         3.1        3.3           .1
 6  Shaft Horsepower                     1868.2      1414.3     1714.1         53.2


                 Test Results for Test SP_1:  02/21/86, 18:39:18
                 For the Interval Between  10  sec and  46  sec

                Average Ship Speed                 3.3    kts
                Average Thrust                 40496.6    lbs
                Average Torque                 41513.5    ft-lbs
                Average RPM                      216.9    RPM
                Average Shaft Horsepower        1714.1    HP
                Average Ice Thickness           1.5417    ft
                Mean Advance Coeff., Js         0.1823
                Thrust Coefficient, Kt          3.060E-01
                Torque Coefficient, Kq          3.690E-02

--------------------------------------------------------------------------------

                          RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs          2.800E+04                       2.614E+04
Thrust Deduction              3.085E-01                       3.545E-01
Propulsive Coeff.             1.664E-01                       1.553E-01

--------------------------------------------------------------------------------

                            Thrust Identity                 Torque Identity

Advance Coefficient             -0.0710                         -0.0827
Thrust Coefficient               3.060E-01                       3.096E-01
Torque Coefficient               3.670E-02                       3.690E-02
Advance Velocity,fps            -2.18                           -2.54
Effective Wake                   1.389E+00                       1.454E+00
Open Prop Eff.                  -9.422E-02                      -1.097E-01
Relative Rotative Eff            9.944E-01                       9.883E-01
Hull Efficiency (Res. Form 1)   -1.776E+00                      -1.524E+00
Hull Efficiency (Res. Form 2)   -1.658E+00                      -1.423E+00
```



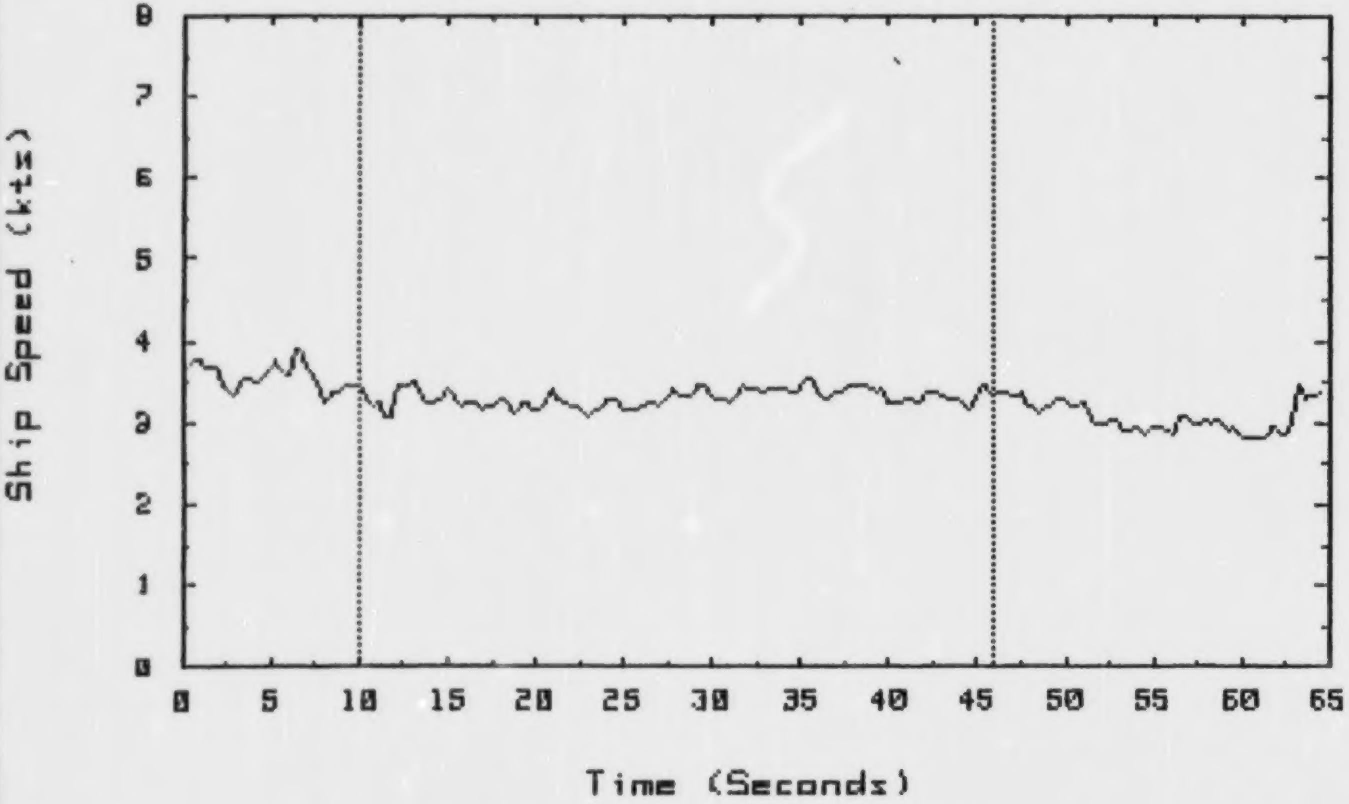
SELF PROPELLED TESTS
SP 1



SELF PROPELLED TESTS
SP 1



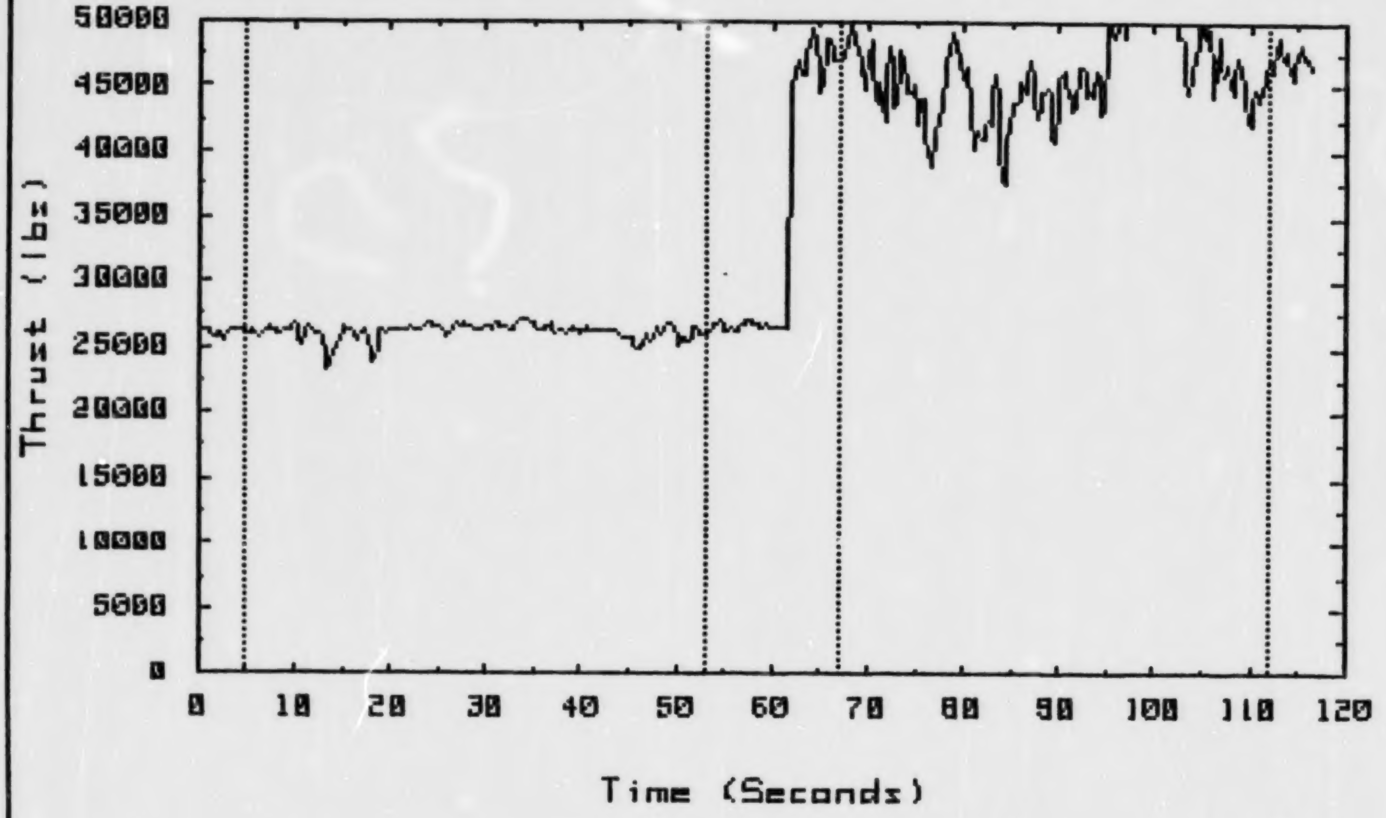
SELF PROPELLED TESTS
SP 1



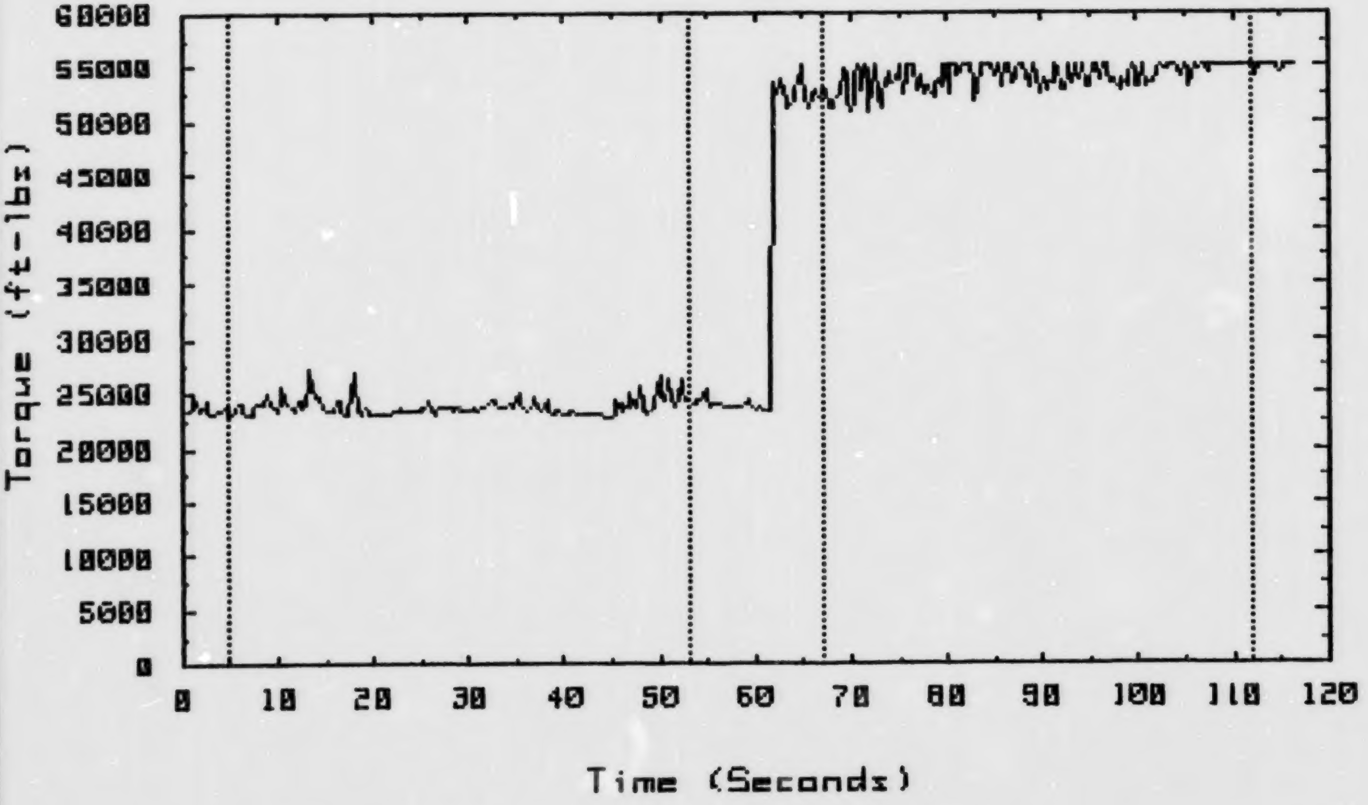
SELF PROPELLED TESTS
SP 1

```
          Test Results for Test SP_2A:  02/21/86, 18:44:46
          For the Interval Between  5  sec and  53  sec

   CHANNEL                               MAXIMUM    MINIMUM     MEAN     STDRD DEV

 1  Thrust (lbs)                         27045.2    23398.3    26125.2      570.5
 2  Torque (ft-lbs)                      27303.2    22788.6    23860.2      815.0
 3  RPM (rpm)                              171.6      163.1      168.6        1.6
 4  Ship Speed (kts)                         2.1        1.4        1.8         .1
 6  Shaft Horsepower                       876.3      720.3      766.0       26.0


          Test Results for Test SP_2A:  02/21/86, 18:44:46
          For the Interval Between  5  sec and  53  sec

         Average Ship Speed                  1.8    kts
         Average Thrust                  26125.2    lbs
         Average Torque                  23860.2    ft-lbs
         Average RPM                       168.6    RPM
         Average Shaft Horsepower          766.0    HP
         Average Ice Thickness            1.5417    ft
         Mean Advance Coeff., Js          0.1247
         Thrust Coefficient, Kt          3.266E-01
         Torque Coefficient, Kq          3.509E-02

-------------------------------------------------------------------------------

                         RESISTANCE FORM 1             RESISTANCE FORM 2

Total Resistance,lbs         2.045E+04                     2.380E+04
Thrust Deduction             2.173E-01                     8.904E-02
Propulsive Coeff.            1.446E-01                     1.683E-01

-------------------------------------------------------------------------------

                           Thrust Identity               Torque Identity

Advance Coefficient          -0.1399                      -0.0315
Thrust Coefficient            3.266E-01                    2.939E-01
Torque Coefficient            3.950E-02                    3.509E-02
Advance Velocity,fps         -3.34                         -.75
Effective Wake                2.122E+00                    1.253E+00
Open Prop Eff.               -1.842E-01                   -4.194E-02
Relative Rotative Eff         1.126E+00                    1.111E+00
Hull Efficiency (Res. Form 1) -6.979E-01                  -3.096E+00
Hull Efficiency (Res. Form 2) -8.122E-01                  -3.603E+00
```

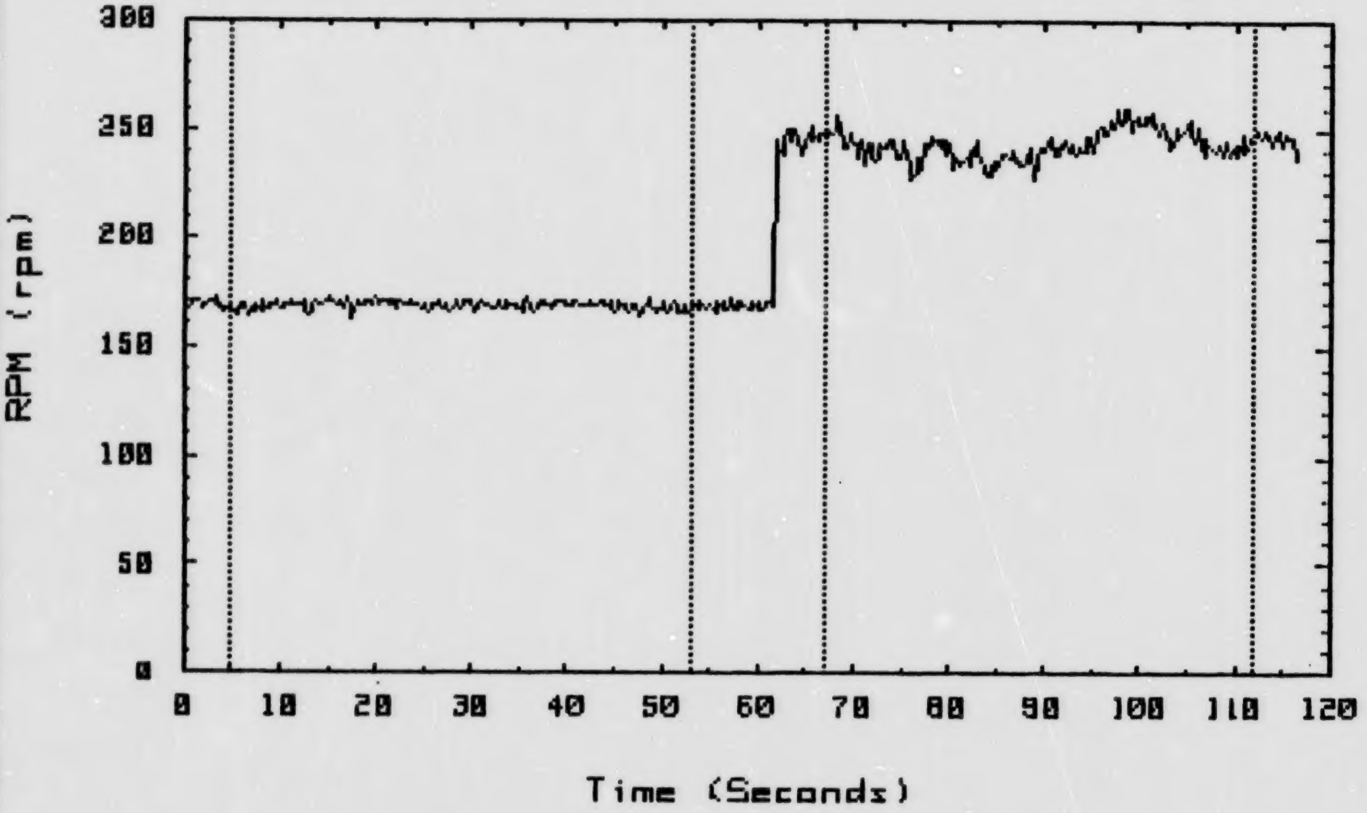
```
                 Test Results for Test SP_2B:  02/21/86, 18:44:46
                 For the Interval Between  67  sec and  112  sec

     CHANNEL                             MAXIMUM     MINIMUM      MEAN      STDRD DEV

   1  Thrust (lbs)                       56362.2     37559.5     46281.7     3607.5
   2  Torque (ft-lbs)                    55112.4     50811.4     54160.6     1085.1
   3  RPM (rpm)                            260.3       227.4       243.2        7.0
   4  Ship Speed (kts)                       5.6         4.0         4.8         .3
   6  Shaft Horsepower                    2686.5      2286.4      2507.8       82.7


                 Test Results for Test SP_2B:  02/21/86, 18:44:46
                 For the Interval Between  67  sec and  112  sec

                 Average Ship Speed                  4.8     kts
                 Average Thrust                  46281.7     lbs
                 Average Torque                  54160.6     ft-lbs
                 Average RPM                       243.2     RPM
                 Average Shaft Horsepower         2507.8     HP
                 Average Ice Thickness            1.5417     ft
                 Mean Advance Coeff., Js          0.2368
                 Thrust Coefficient, Kt          2.782E-01
                 Torque Coefficient, Kq          3.830E-02
---------------------------------------------------------------------------------

                          RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs          3.542E+04                       2.986E+04
Thrust Deduction              2.348E-01                       3.549E-01
Propulsive Coeff.             2.095E-01                       1.766E-01
---------------------------------------------------------------------------------

                          Thrust Identity                 Torque Identity

Advance Coefficient           0.0186                          -0.1215
Thrust Coefficient            2.782E-01                        3.213E-01
Torque Coefficient            3.332E-02                        3.830E-02
Advance Velocity,fps           .64                            -4.19
Effective Wake                9.213E-01                        1.513E+00
Open Prop Eff.                2.476E-02                       -1.604E-01
Relative Rotative Eff         8.700E-01                        8.658E-01
Hull Efficiency (Res. Form 1) 9.725E+00                       -1.492E+00
Hull Efficiency (Res. Form 2) 8.199E+00                       -1.258E+00
```



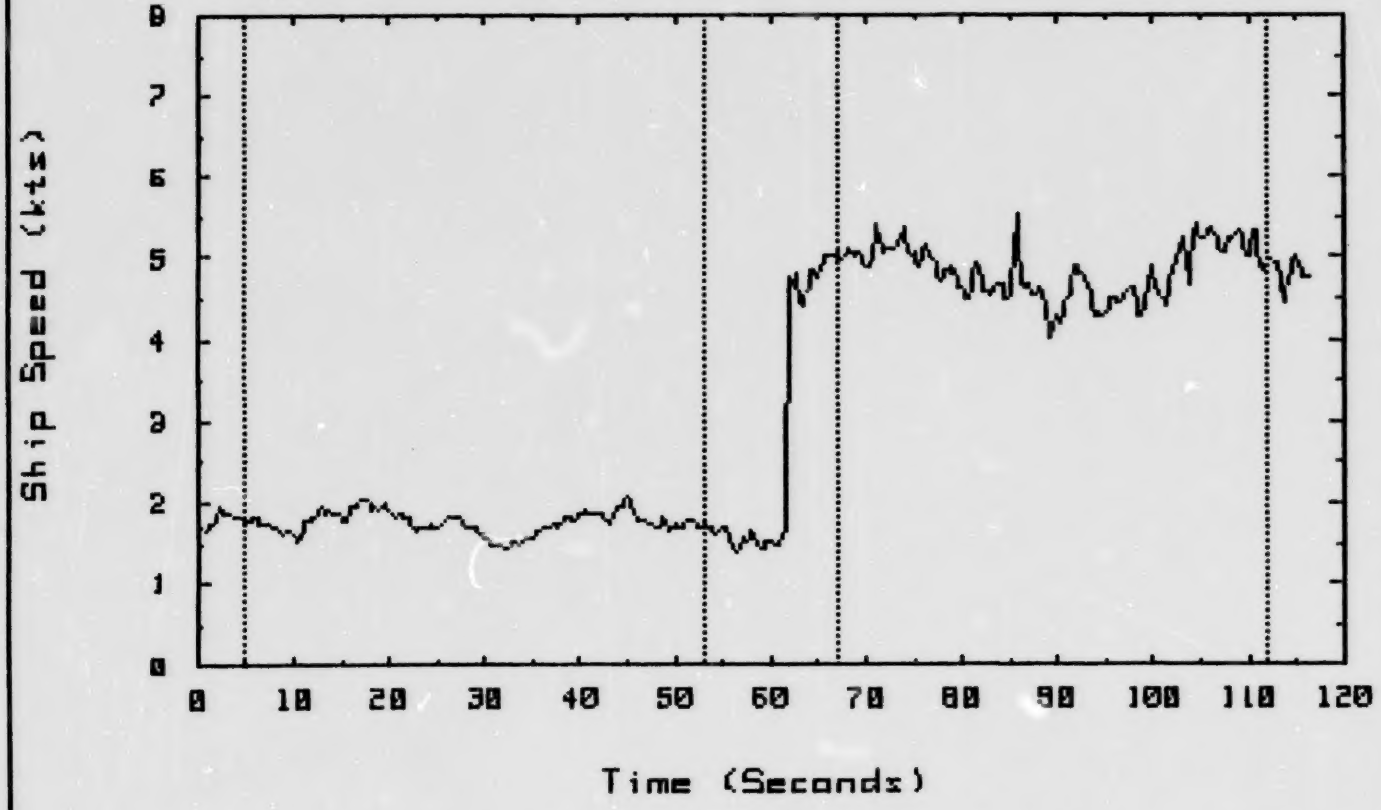
SELF PROPELLED TESTS
SP 2



SELF PROPELLED TESTS
SP 2

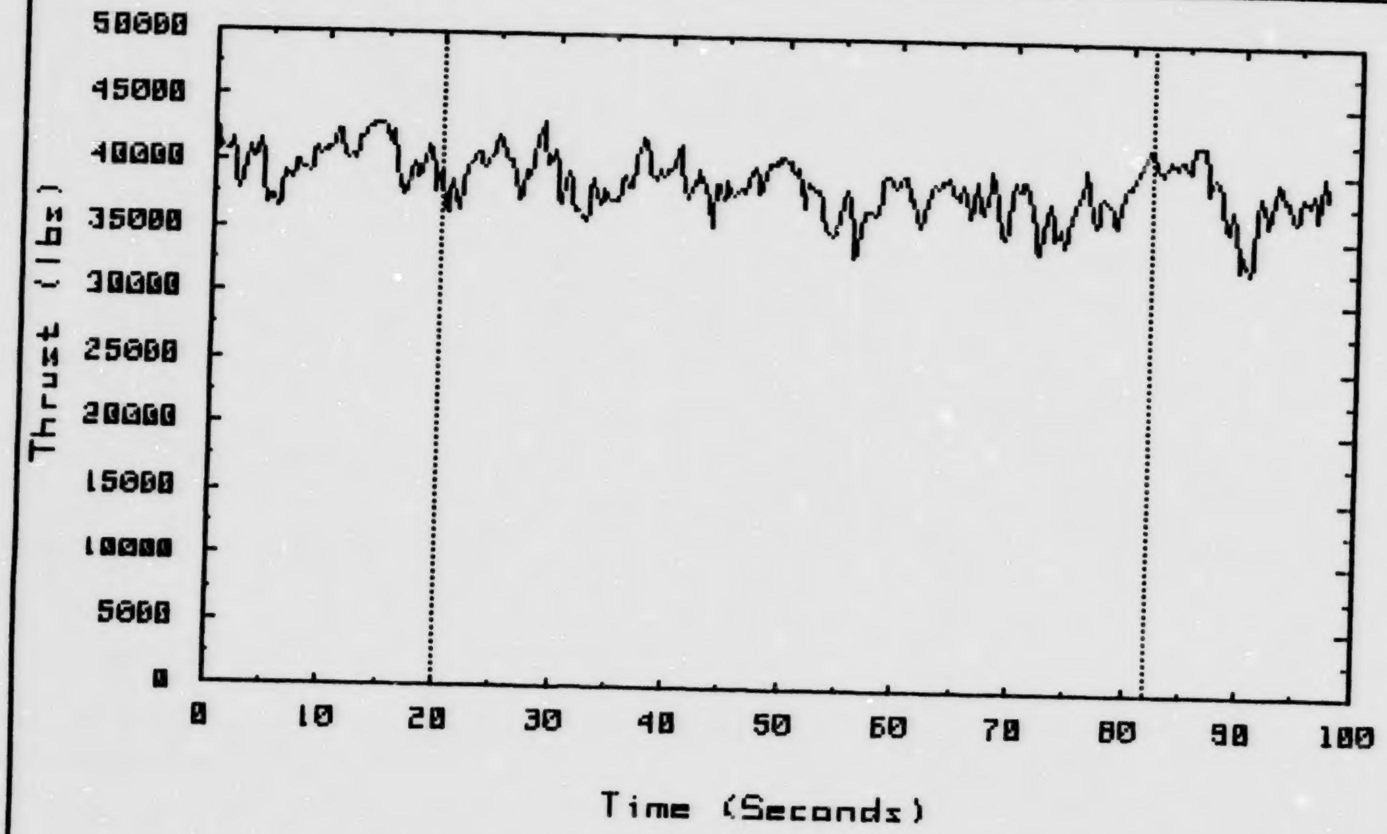


SELF PROPELLED TESTS
SP 2

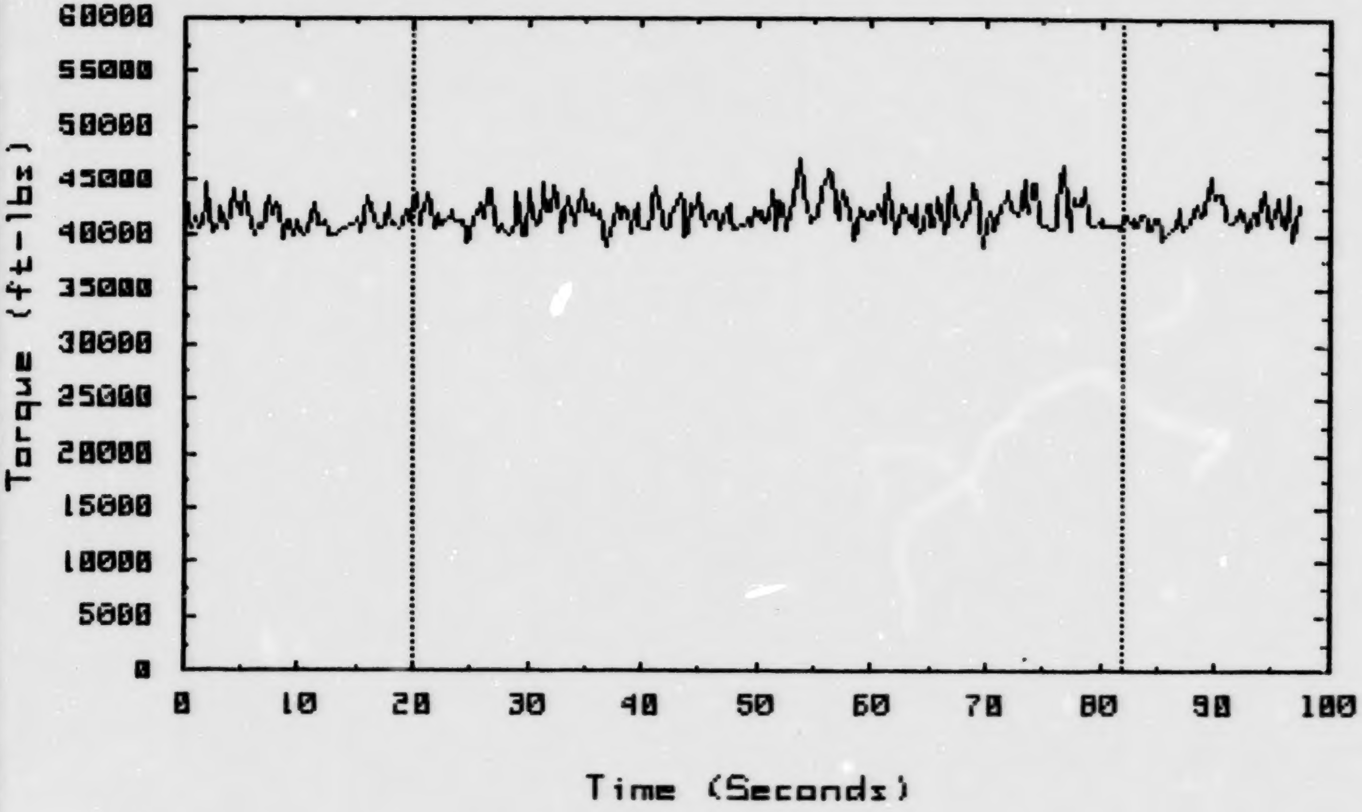


SELF PROPELLED TESTS
SP 2

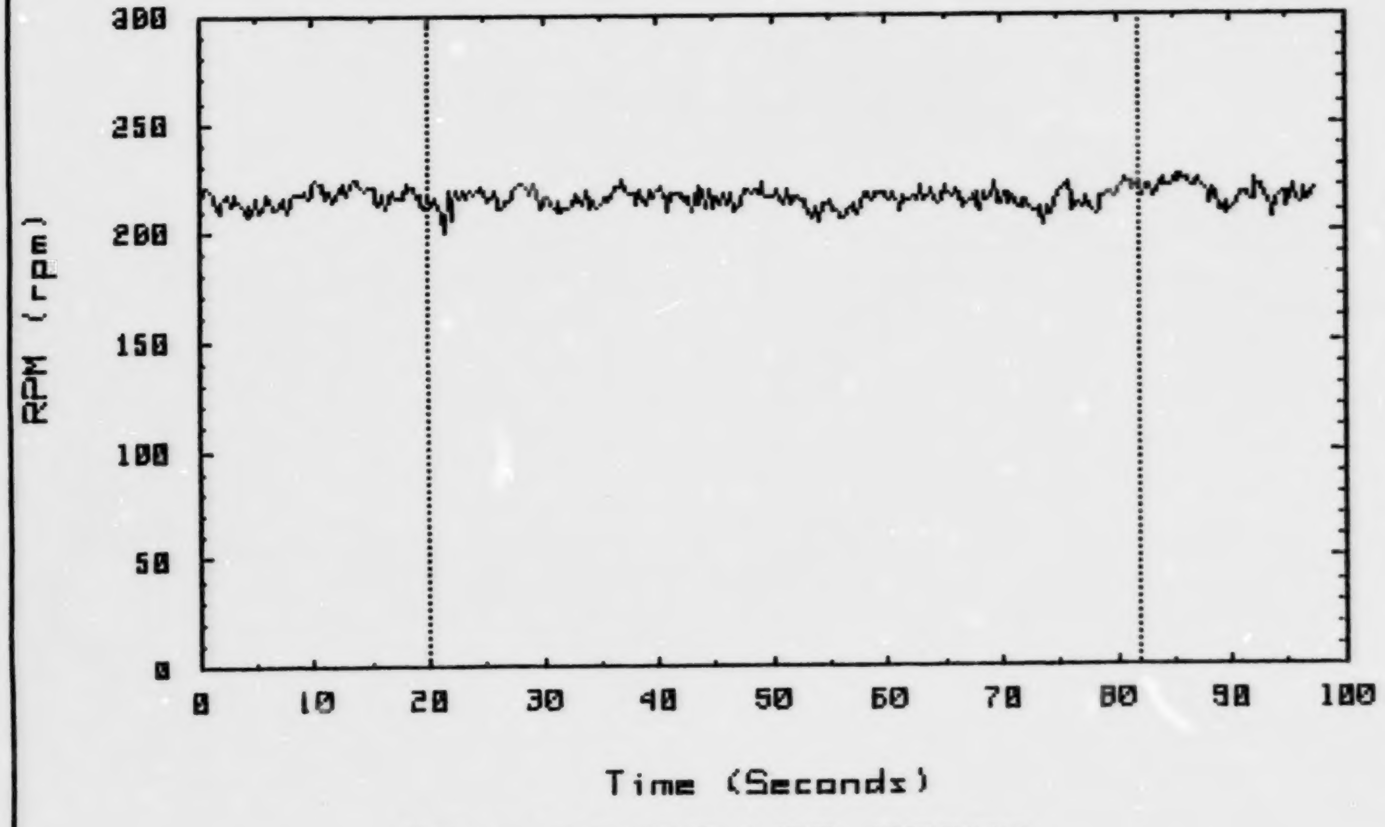
```
            Test Results for Test SP_3:  02/21/86, 18:52:35
            For the Interval Between  20  sec and  82  sec

  CHANNEL                              MAXIMUM     MINIMUM       MEAN     STDRD DEV

 1  Thrust (lbs)                       43148.2     33344.3     38443.2      1809.0
 2  Torque (ft-lbs)                    47071.5     38977.2     42095.5      1406.8
 3  RPM (rpm)                            223.9       200.0       215.0         4.0
 4  Ship Speed (kts)                       4.3         3.2         3.7          .2
 6  Shaft Horsepower                    1885.9      1584.1      1722.8        50.9


            Test Results for Test SP_3:  02/21/86, 18:52:35
            For the Interval Between  20  sec and  82  sec

           Average Ship Speed                   3.7   kts
           Average Thrust                   38443.2   lbs
           Average Torque                   42095.5   ft-lbs
           Average RPM                        215.0   RPM
           Average Shaft Horsepower          1722.8   HP
           Average Ice Thickness             1.5417   ft
           Mean Advance Coeff., Js           0.2049
           Thrust Coefficient, Kt            2.956E-01
           Torque Coefficient, Kq            3.808E-02

--------------------------------------------------------------------------------

                          RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs           2.984E+04                      2.692E+04
Thrust Deduction               2.238E-01                      2.997E-01
Propulsive Coeff.              1.964E-01                      1.772E-01

--------------------------------------------------------------------------------

                            Thrust Identity                Torque Identity

Advance Coefficient            -0.0370                        -0.1155
Thrust Coefficient              2.956E-01                      3.195E-01
Torque Coefficient              3.539E-02                      3.808E-02
Advance Velocity,fps           -1.13                          -3.52
Effective Wake                  1.181E+00                      1.564E+00
Open Prop Eff.                 -4.925E-02                     -1.526E-01
Relative Rotative Eff           9.292E-01                      9.252E-01
Hull Efficiency (Res. Form 1)  -4.293E+00                     -1.377E+00
Hull Efficiency (Res. Form 2)  -3.873E+00                     -1.242E+00
```



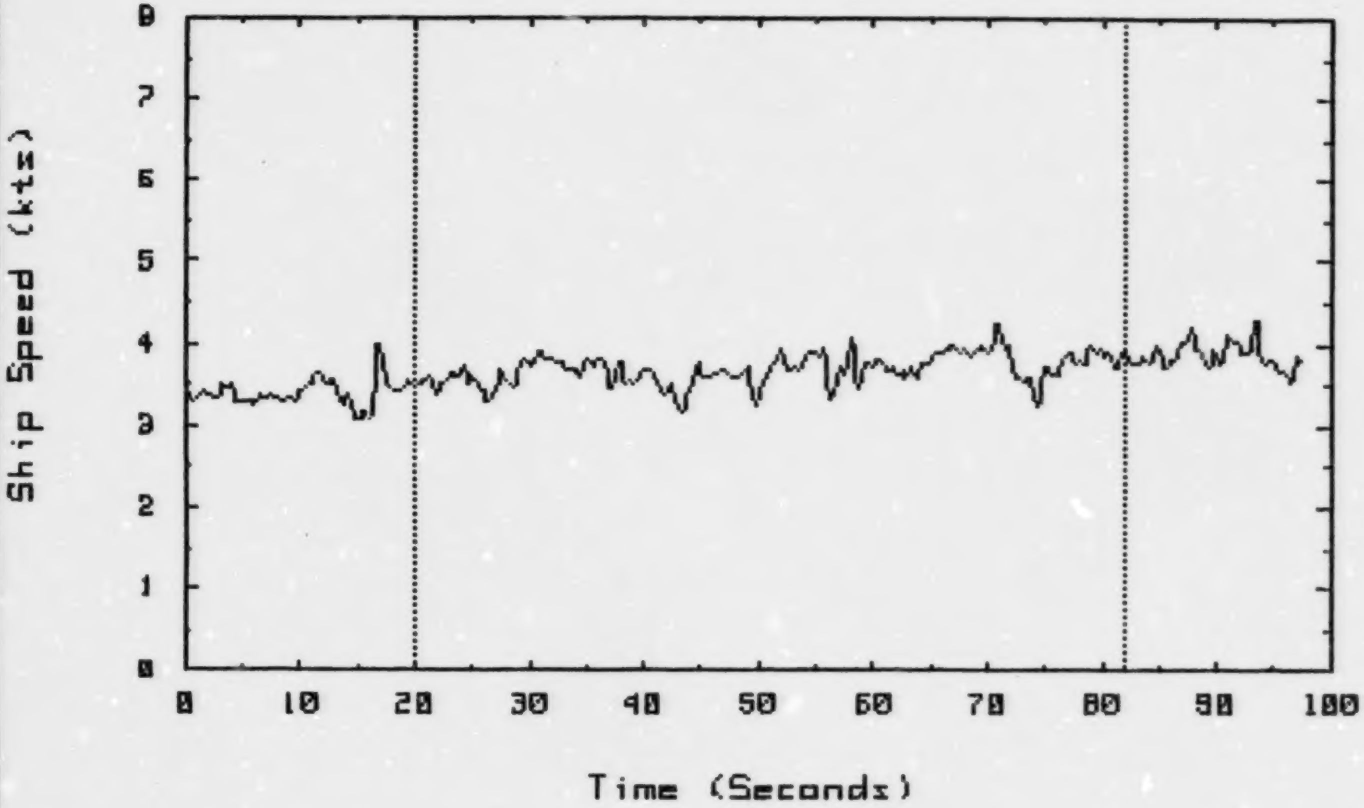
SELF PROPELLED TESTS
SP 3



SELF PROPELLED TESTS
SP 3

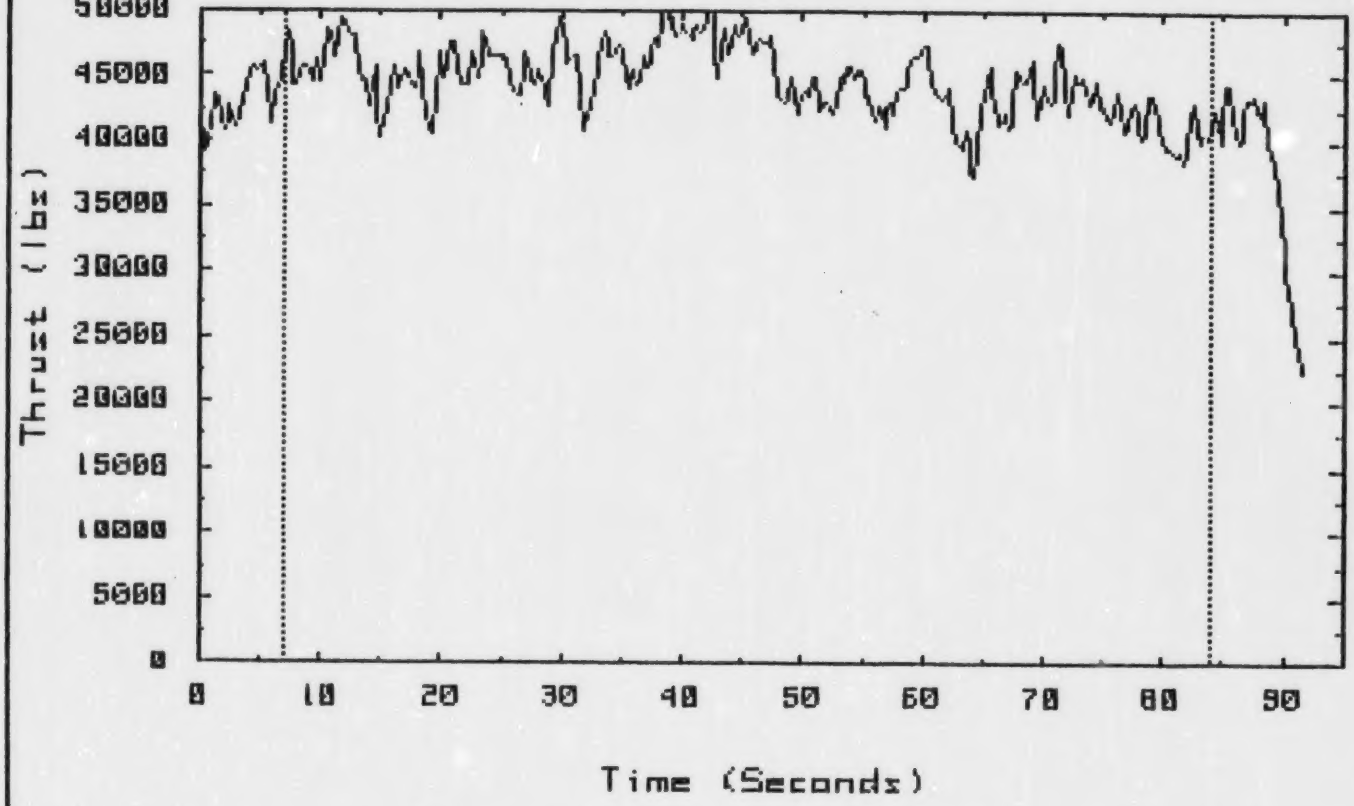


SELF PROPELLED TESTS
SP 3

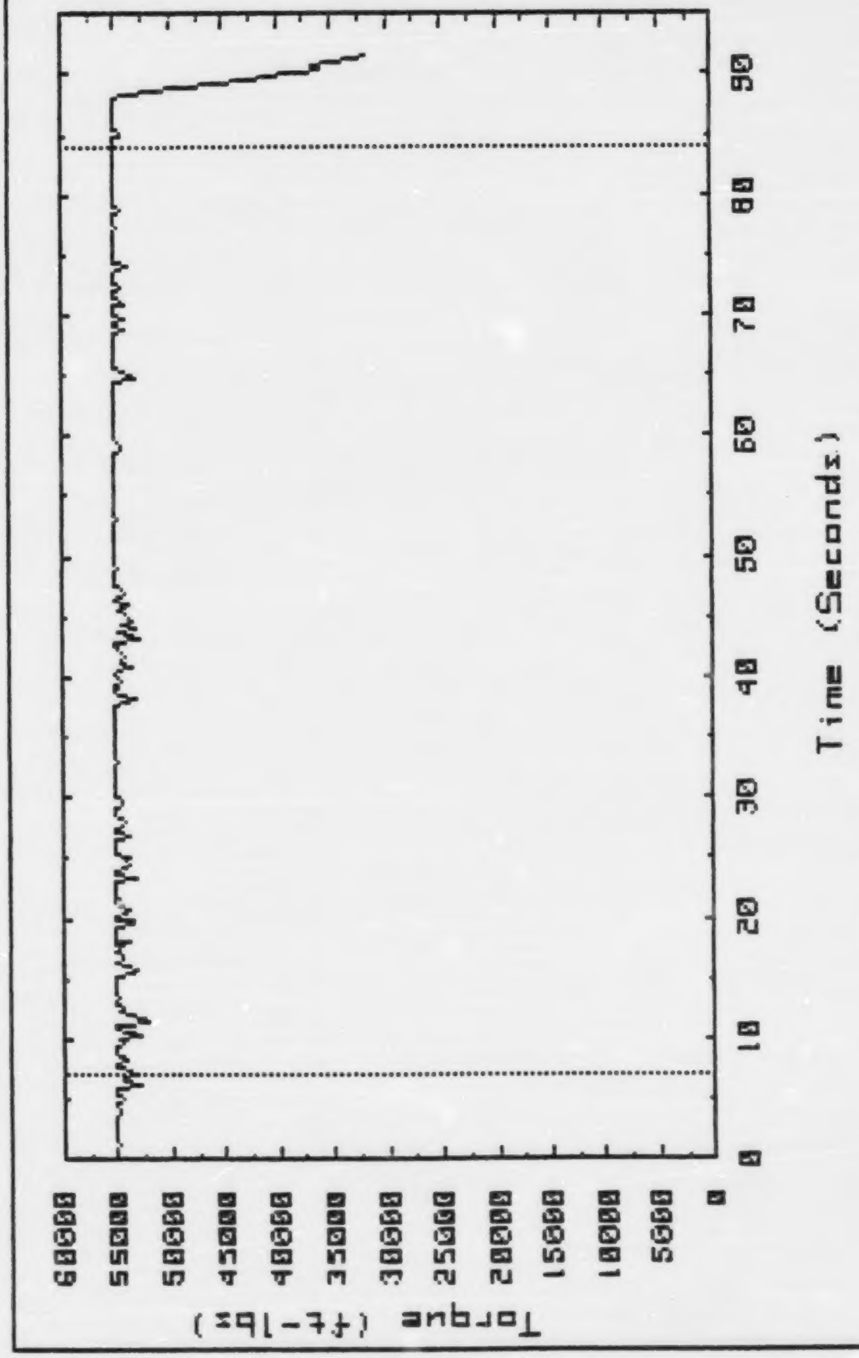


SELF PROPELLED TESTS
SP 3

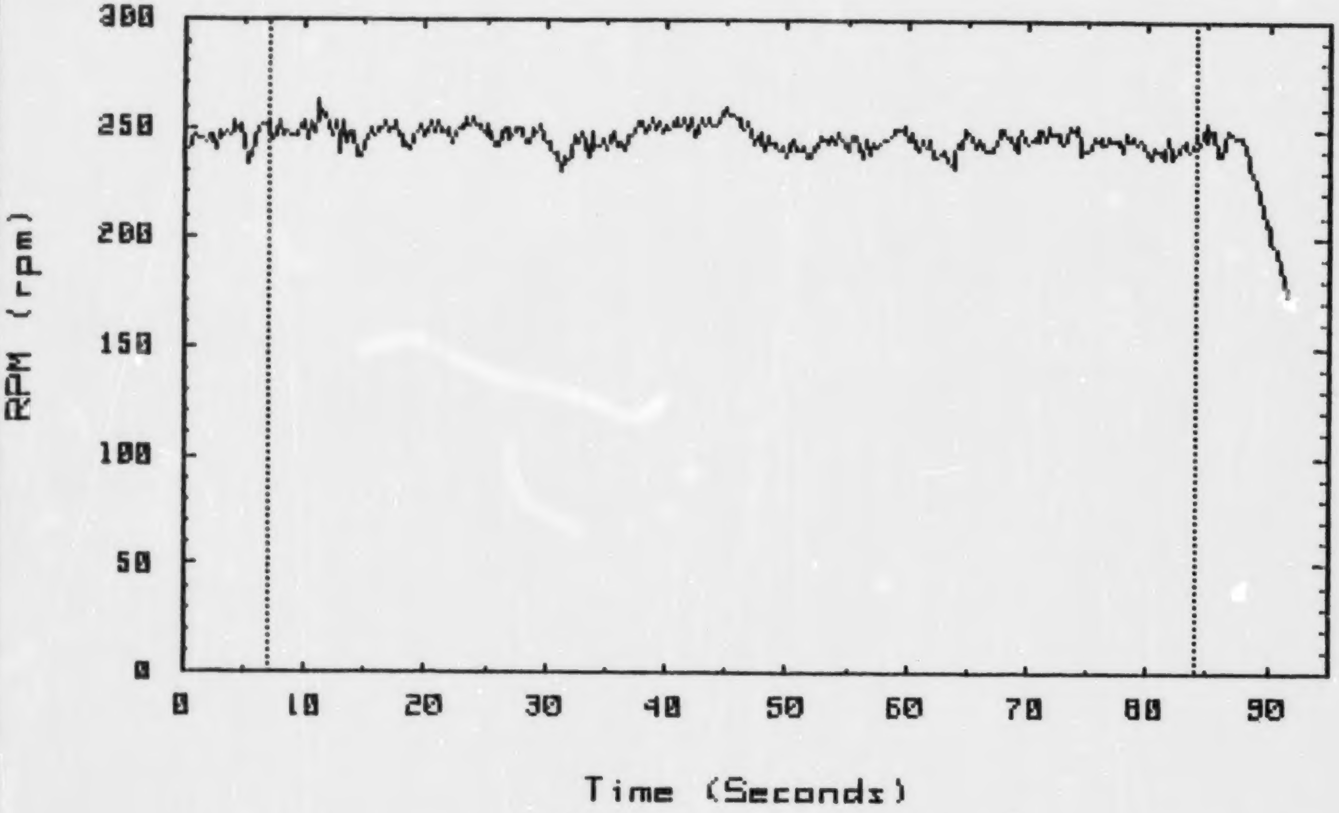
```
              Test Results for Test SP_4:  02/21/86, 19:11:00
              For the Interval Between  7  sec and  84  sec

   CHANNEL                          MAXIMUM      MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                    50820.8      37370.1      44686.6      2624.3
 2  Torque (ft-lbs)                 55112.4      52280.7      54841.3       514.4
 3  RPM (rpm)                         262.0        229.6        246.0         5.1
 4  Ship Speed (kts)                    6.7          4.5          5.5          .4
 6  Shaft Horsepower                 2721.3       2409.4       2568.0        47.1


              Test Results for Test SP_4:  02/21/86, 19:11:00
              For the Interval Between  7  sec and  84  sec

             Average Ship Speed                  5.5    kts
             Average Thrust                  44686.6    lbs
             Average Torque                  54841.3    ft-lbs
             Average RPM                       246.0    RPM
             Average Shaft Horsepower         2568.0    HP
             Average Ice Thickness            1.5417    ft
             Mean Advance Coeff., Js          0.2688
             Thrust Coefficient, Kt           2.626E-01
             Torque Coefficient, Kq           3.791E-02

--------------------------------------------------------------------------------

                         RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs        3.899E+04                      3.219E+04
Thrust Deduction            1.274E-01                      2.796E-01
Propulsive Coeff.           2.585E-01                      2.134E-01

--------------------------------------------------------------------------------

                           Thrust Identity                Torque Identity

Advance Coefficient         0.0670                        -0.1109
Thrust Coefficient          2.626E-01                      3.181E-01
Torque Coefficient          3.159E-02                      3.791E-02
Advance Velocity,fps        2.34                          -3.86
Effective Wake              7.506E-01                      1.413E+00
Open Prop Eff.              8.869E-02                     -1.467E-01
Relative Rotative Eff       8.331E-01                      8.255E-01
Hull Efficiency (Res. Form 1)  3.498E+00                  -2.114E+00
Hull Efficiency (Res. Form 2)  2.888E+00                  -1.746E+00
```



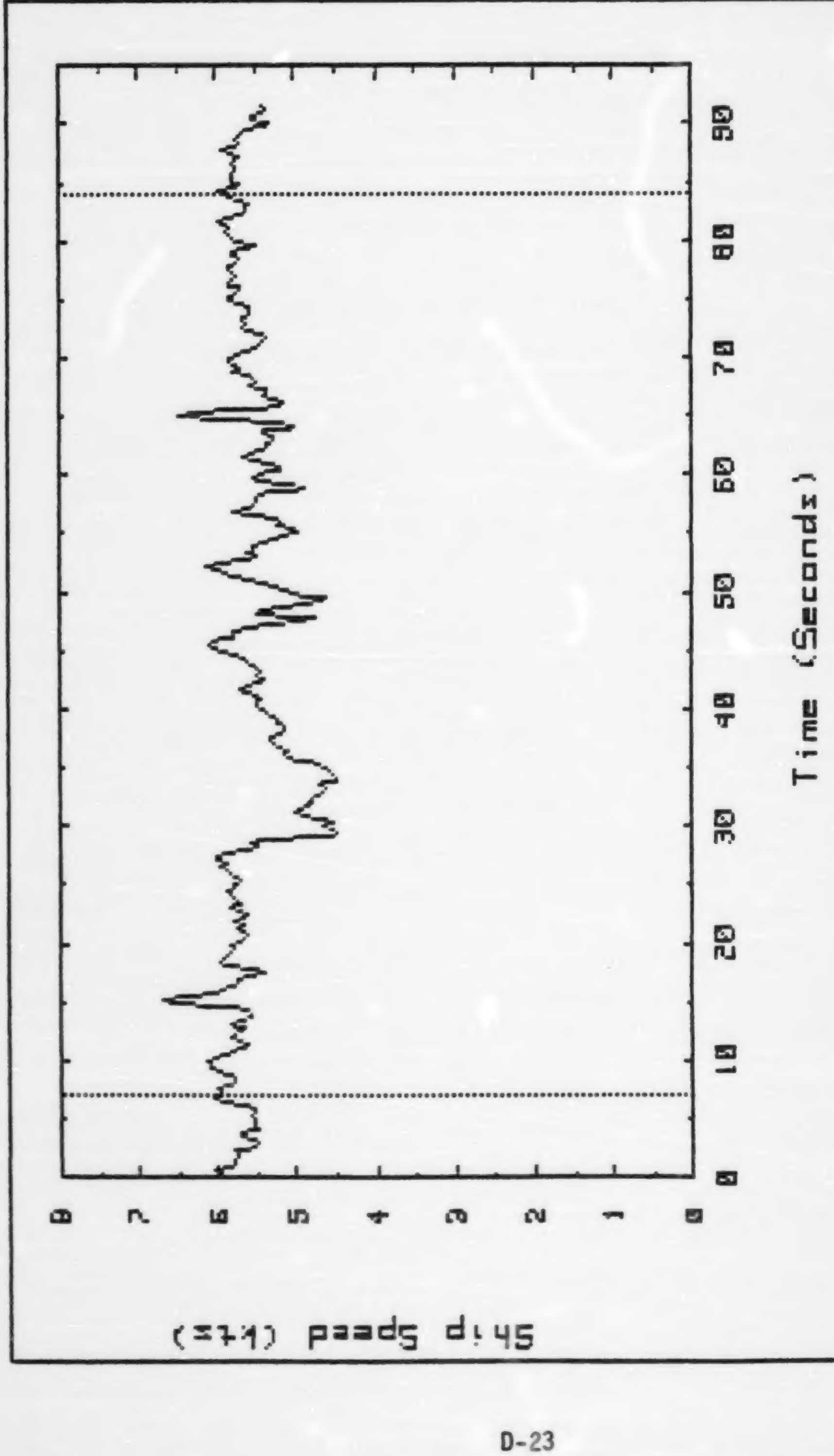
SELF PROPELLED TESTS
SP 4



SELF PROPELLED TESTS
SP 4



SELF PROPELLED TESTS
SP 4

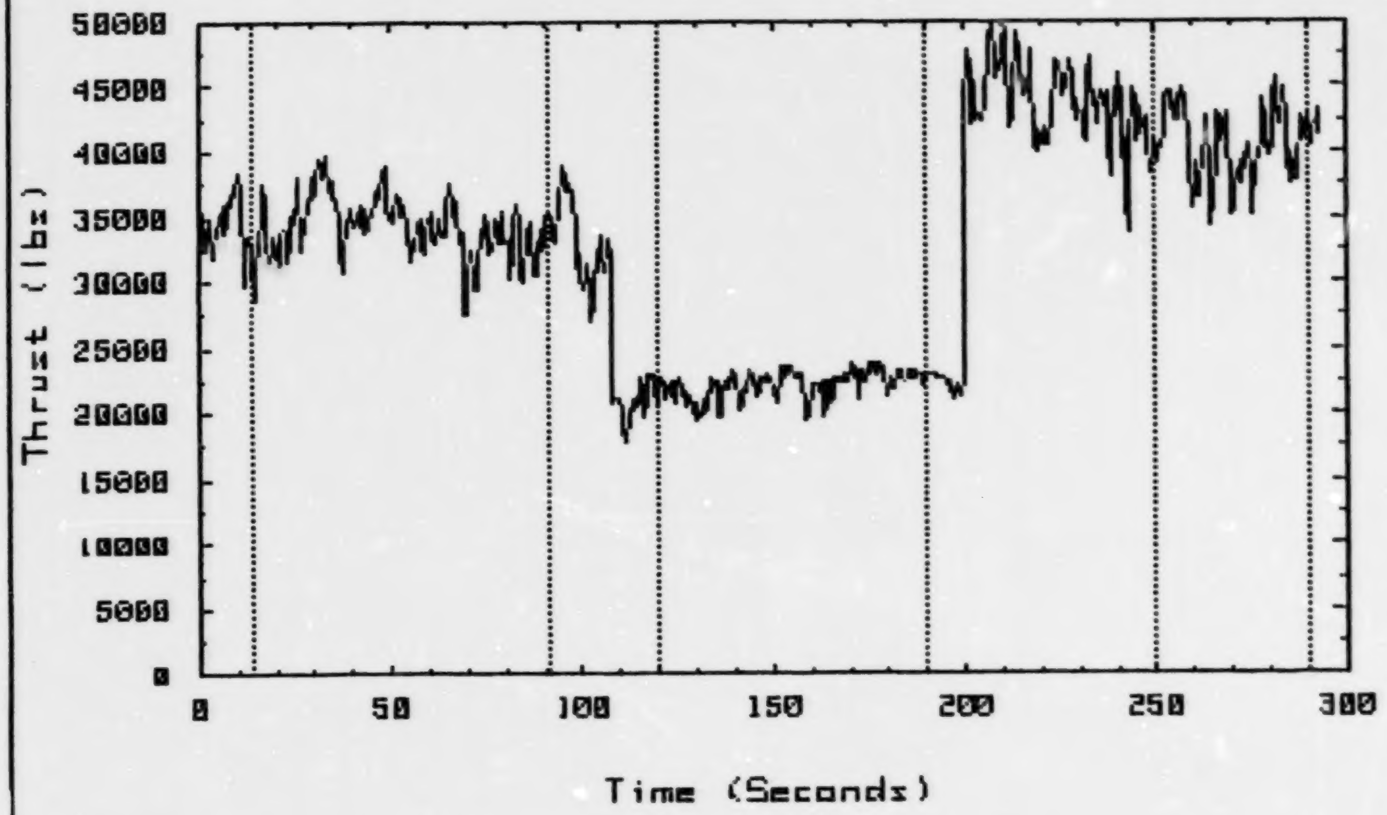


SELF PROPELLED TESTS
SP 4

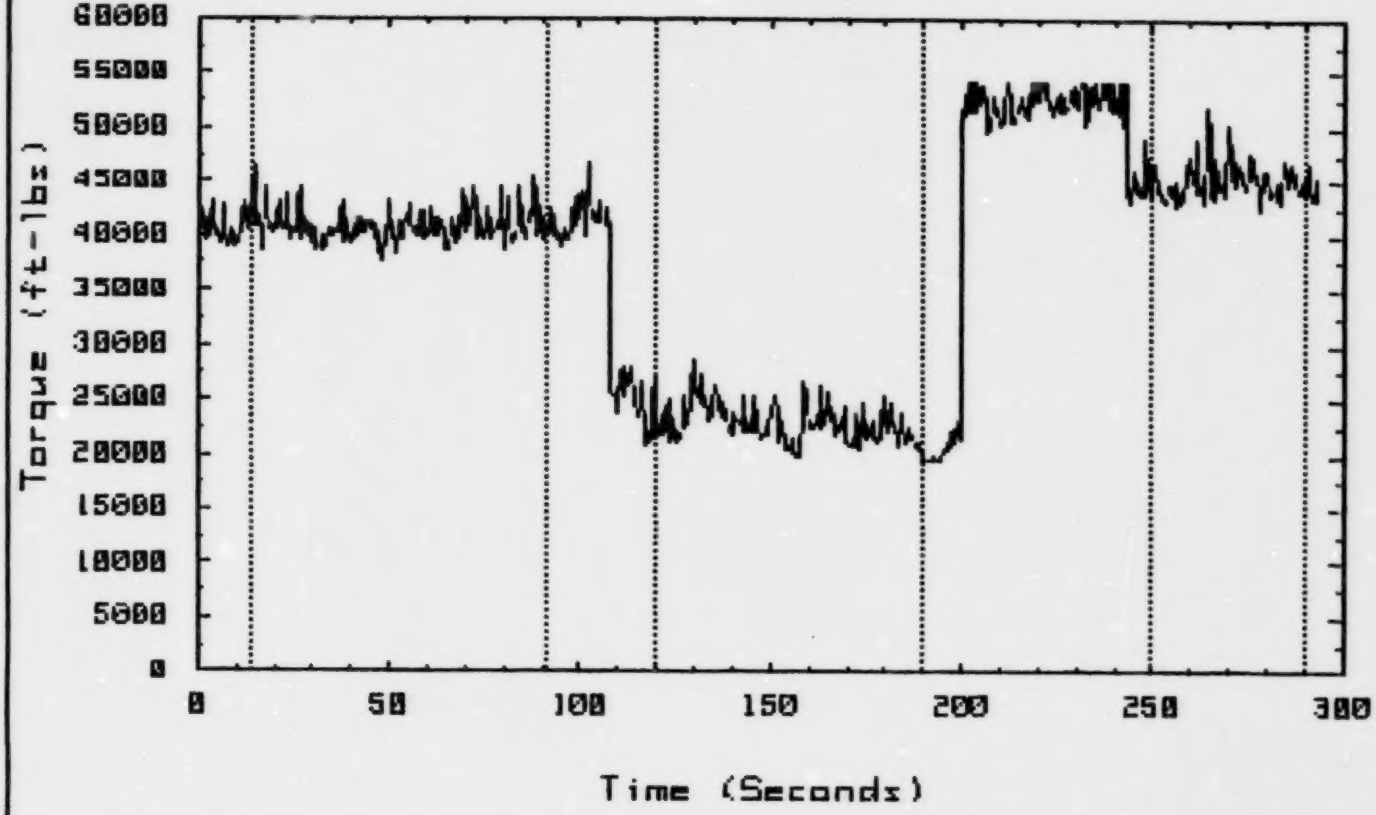
```
          Test Results for Test SP_SA:  02/21/86, 20:06:29
          For the Interval Between  14  sec and  91  sec

   CHANNEL                              MAXIMUM      MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                        39682.8      27605.5     34293.8      2229.0
 2  Torque (ft-lbs)                     46333.8      37625.1     40946.9      1355.6
 3  RPM (rpm)                             230.7        203.8       216.9         4.3
 4  Ship Speed (kts)                        6.7          5.1         5.7          .3
 6  Shaft Horsepower                     1854.7       1551.3      1690.1        43.3


          Test Results for Test SP_SA:  02/21/86, 20:06:29
          For the Interval Between  14  sec and  91  sec

         Average Ship Speed                    5.7   kts
         Average Thrust                    34293.8   lbs
         Average Torque                    40946.9   ft-lbs
         Average RPM                         216.9   RPM
         Average Shaft Horsepower           1690.1   HP
         Average Ice Thickness              1.5833   ft
         Mean Advance Coeff., Js            0.3122
         Thrust Coefficient, Kt            2.592E-01
         Torque Coefficient, Kq            3.641E-02

------------------------------------------------------------------------------

                         RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs        4.101E+04                      3.359E+04
Thrust Deduction           -1.960E-01                      2.053E-02
Propulsive Coeff.           4.230E-01                      3.464E-01

------------------------------------------------------------------------------

                           Thrust Identity                Torque Identity

Advance Coefficient         0.0775                         -0.0688
Thrust Coefficient          2.592E-01                       3.054E-01
Torque Coefficient          3.122E-02                       3.641E-02
Advance Velocity,fps        2.38                           -2.11
Effective Wake              7.518E-01                       1.221E+00
Open Prop Eff.              1.024E-01                      -9.138E-02
Relative Rotative Eff       8.574E-01                       8.487E-01
Hull Efficiency (Res. Form 1)  4.819E+00                   -5.424E+00
Hull Efficiency (Res. Form 2)  3.947E+00                   -4.442E+00
```

```
               Test Results for Test SP_SB:  02/21/86, 20:06:29
               For the Interval Between  120  sec and  190  sec

   CHANNEL                           MAXIMUM     MINIMUM       MEAN      STDRD DEV

  1  Thrust (lbs)                    23769.2     19554.0     22254.6        964.4
  2  Torque (ft-lbs)                 28462.2     19646.7     22896.6       1590.2
  3  RPM (rpm)                         179.3       149.4       168.2          3.4
  4  Ship Speed (kts)                    4.7         3.6         4.1           .2
  6  Shaft Horsepower                  882.8       620.6       733.1         47.8


               Test Results for Test SP_SB:  02/21/86, 20:06:29
               For the Interval Between  120  sec and  190  sec

              Average Ship Speed                   4.1    kts
              Average Thrust                   22254.6    lbs
              Average Torque                   22896.6    ft-lbs
              Average RPM                        168.2    RPM
              Average Shaft Horsepower           733.1    HP
              Average Ice Thickness             1.5833    ft
              Mean Advance Coeff., Js           0.2896
              Thrust Coefficient, Kt         2.795E-01
              Torque Coefficient, Kq         3.383E-02

----------------------------------------------------------------------------------

                          RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs            3.289E+04                       2.890E+04
Thrust Deduction               -4.778E-01                      -2.984E-01
Propulsive Coeff.               5.627E-01                       4.944E-01

----------------------------------------------------------------------------------

                             Thrust Identity                 Torque Identity

Advance Coefficient             0.0144                         0.0044
Thrust Coefficient              2.795E-01                      2.827E-01
Torque Coefficient              3.347E-02                      3.383E-02
Advance Velocity,fps             .34                            .11
Effective Wake                  9.504E-01                      9.347E-01
Open Prop Eff.                  1.910E-02                      5.977E-03
Relative Rotative Eff           9.894E-01                      9.889E-01
Hull Efficiency (Res. Form 1)   2.977E+01                      9.682E+01
Hull Efficiency (Res. Form 2)   2.616E+01                      8.507E+01
```

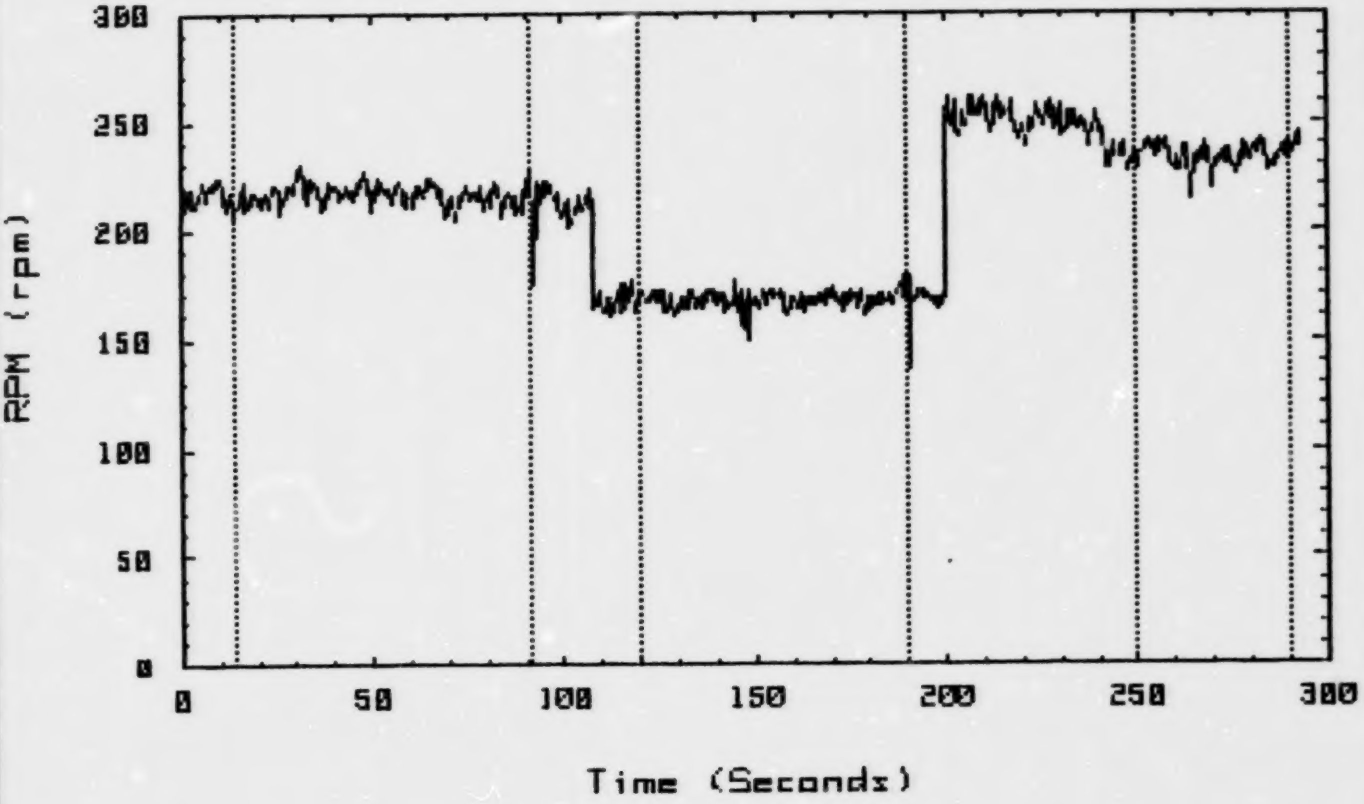
```
            Test Results for Test SP_SC:  02/21/86, 20:06:29
            For the Interval Between  250  sec and  290  sec

  CHANNEL                            MAXIMUM     MINIMUM      MEAN     STDRD DEV

 1  Thrust (lbs)                     45792.5     34283.5     40594.7     2653.3
 2  Torque (ft-lbs)                  51970.4     42620.6     45333.3     1538.0
 3  RPM (rpm)                          242.4       214.0       233.9        4.9
 4  Ship Speed (kts)                     6.9         5.7         6.3         .2
 6  Shaft Horsepower                  2223.3      1913.7      2017.7       44.6


            Test Results for Test SP_SC:  02/21/86, 20:06:29
            For the Interval Between  250  sec and  290  sec

           Average Ship Speed                  6.3   kts
           Average Thrust                  40594.7   lbs
           Average Torque                  45333.3   ft-lbs
           Average RPM                       233.9   RPM
           Average Shaft Horsepower         2017.7   HP
           Average Ice Thickness            1.5833   ft
           Mean Advance Coeff., Js          0.3219
           Thrust Coefficient, Kt          2.638E-01
           Torque Coefficient, Kq          3.466E-02

--------------------------------------------------------------------------------

                   RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs          4.438E+04                  3.602E+04
Thrust Deduction             -9.326E-02                  1.127E-01
Propulsive Coeff.             4.264E-01                  3.460E-01

--------------------------------------------------------------------------------

                       Thrust Identity              Torque Identity

Advance Coefficient          0.0633                     -0.0192
Thrust Coefficient           2.638E-01                   2.901E-01
Torque Coefficient           3.172E-02                   3.466E-02
Advance Velocity,fps         2.10                       -.64
Effective Wake               8.033E-01                   1.060E+00
Open Prop Eff.               8.382E-02                  -2.554E-02
Relative Rotative Eff        9.151E-01                   9.094E-01
Hull Efficiency (Res. Form 1) 5.558E+00                 -1.832E+01
Hull Efficiency (Res. Form 2) 4.511E+00                 -1.487E+01
```



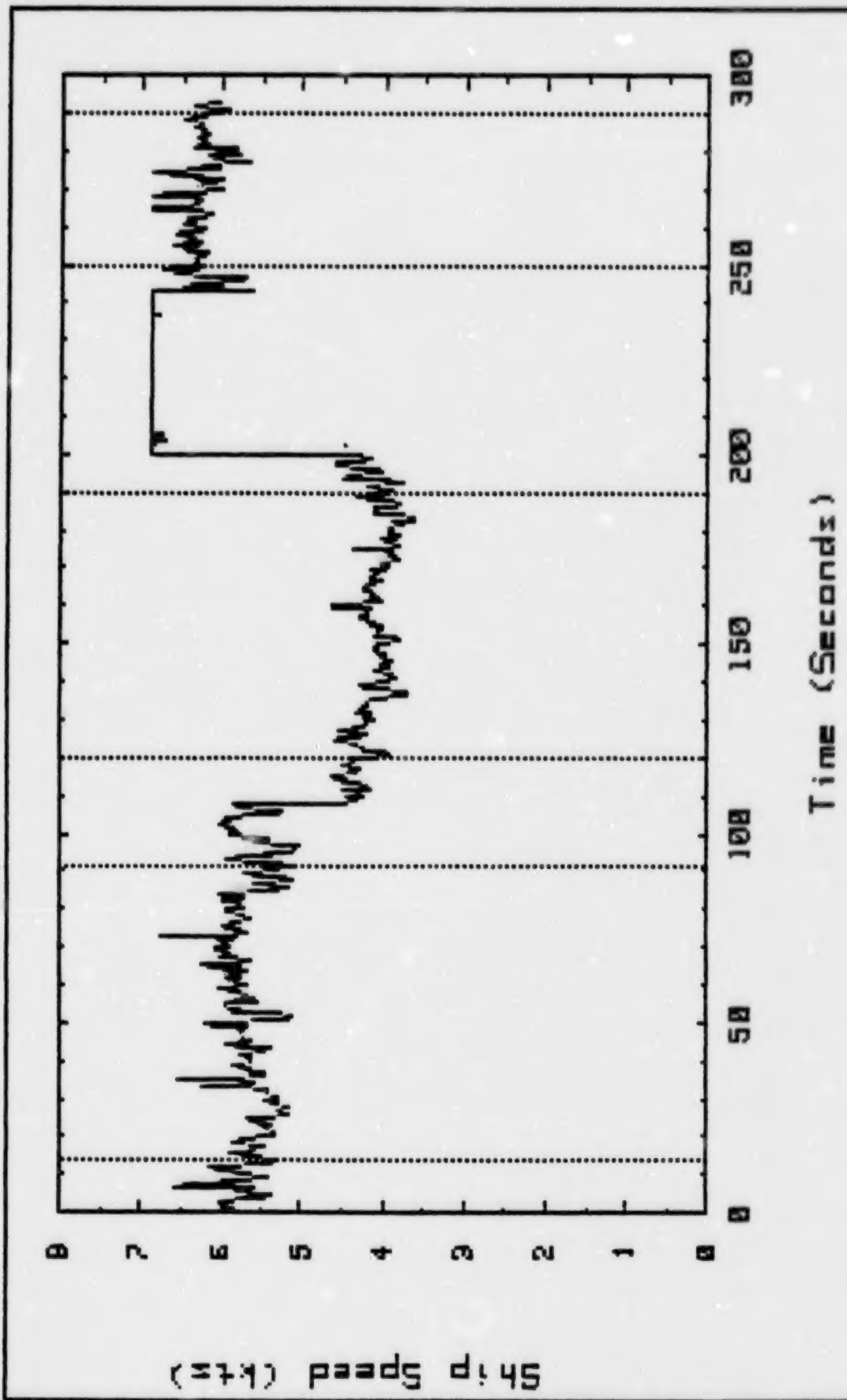
SELF PROPELLED TEST
SP 5



SELF PROPELLED TEST
SP 5

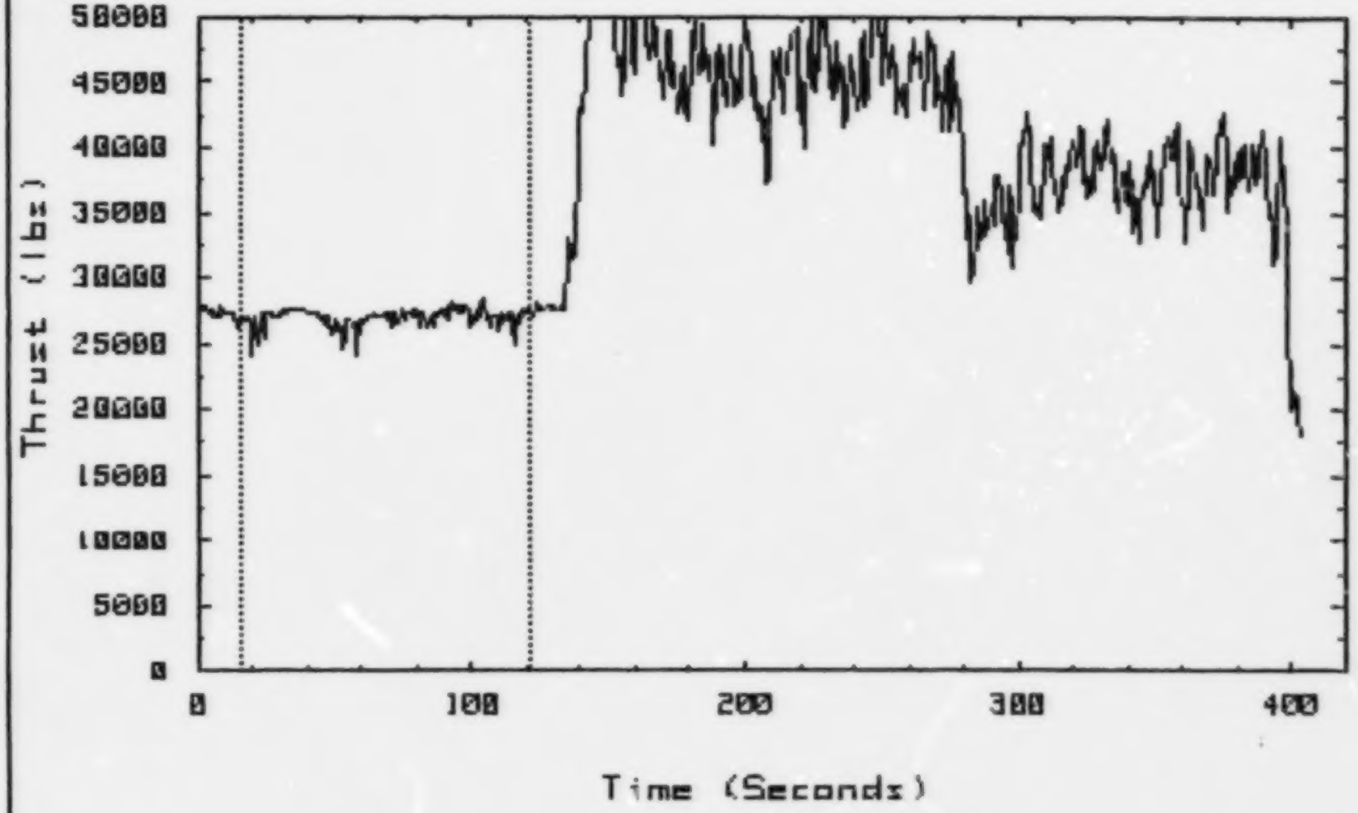


SELF PROPELLED TEST
SP 5

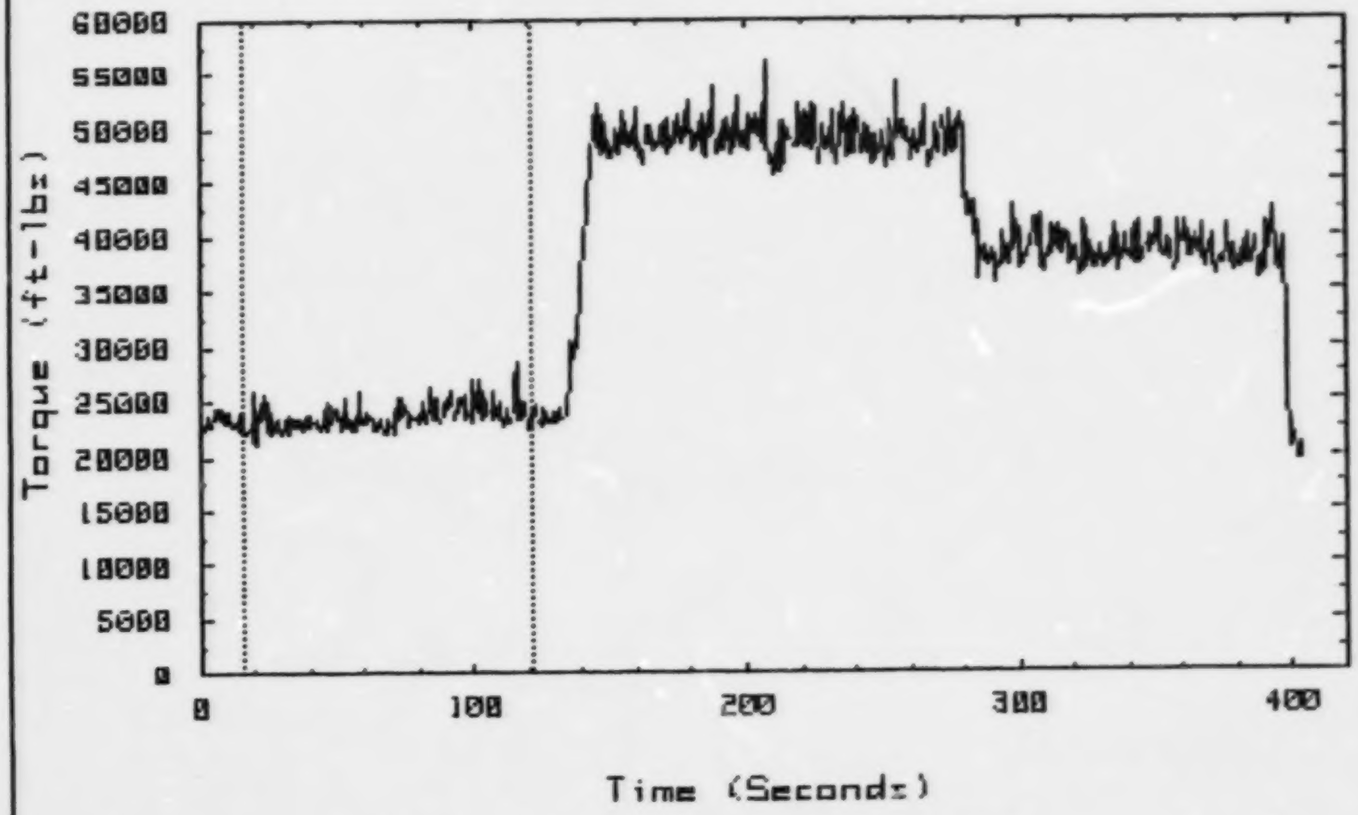


SELF PROPELLED TEST
SP 5

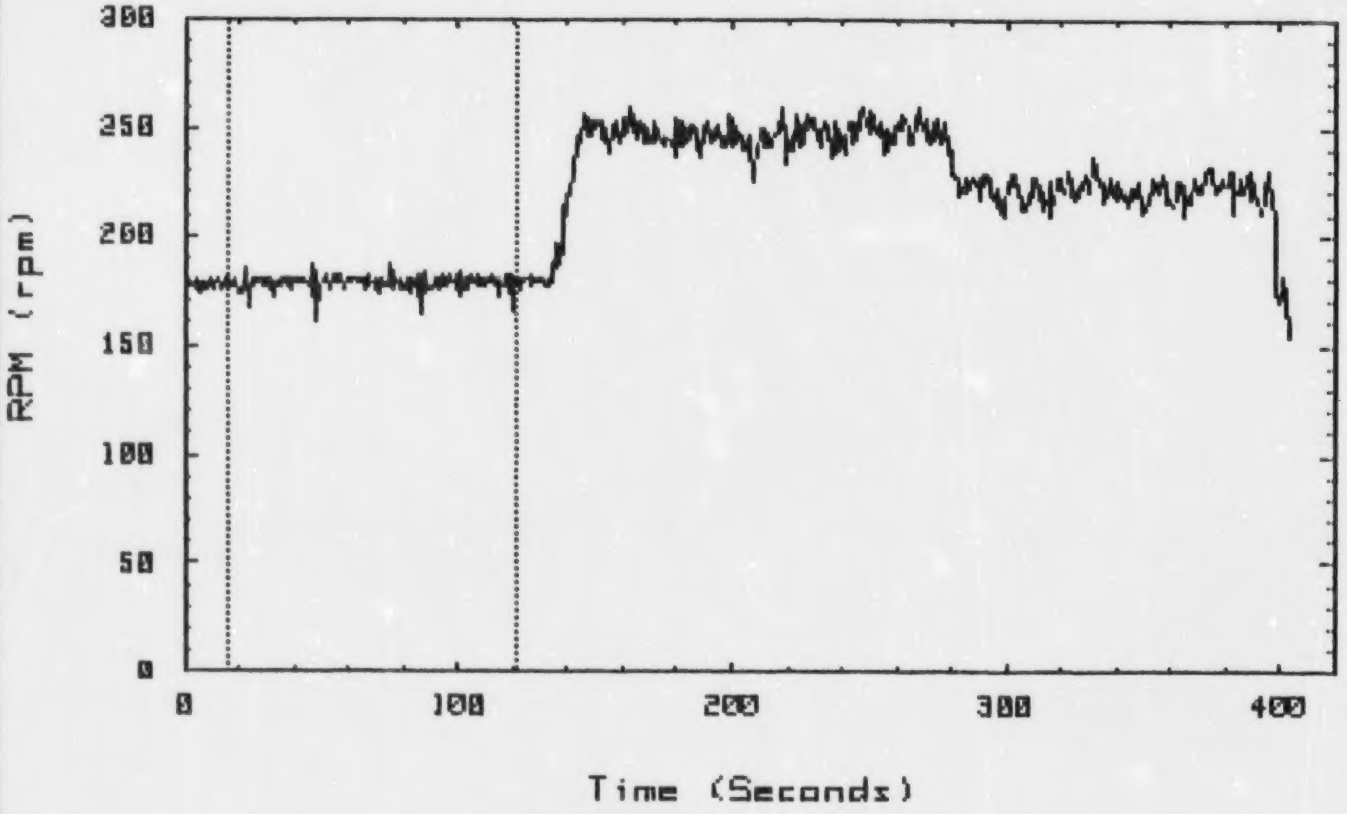
```
                    Test Results for Test SP_6A:  02/23/86, 13:54:43
                    For the Interval Between  16  sec and  122  sec

  CHANNEL                             MAXIMUM      MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                      28294.3      24084.8      27015.1       607.3
 2  Torque (ft-lbs)                   28536.6      21262.5      23727.2       953.9
 3  RPM (rpm)                           186.6        161.1        178.7         2.6
 4  Ship Speed (kts)                      4.0          2.9          3.3          .2
 6  Shaft Horsepower                    961.6        717.5        807.1        33.7


                    Test Results for Test SP_6A:  02/23/86, 13:54:43
                    For the Interval Between  16  sec and  122  sec

                   Average Ship Speed                  3.3   kts
                   Average Thrust                  27015.1   lbs
                   Average Torque                  23727.2   ft-lbs
                   Average RPM                       178.7   RPM
                   Average Shaft Horsepower          807.1   HP
                   Average Ice Thickness            1.2917   ft
                   Mean Advance Coeff., Js          0.2180
                   Thrust Coefficient, Kt          3.009E-01
                   Torque Coefficient, Kq          3.109E-02

----------------------------------------------------------------------------------

                           RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs          2.190E+04                      2.014E+04
Thrust Deduction              1.893E-01                      2.544E-01
Propulsive Coeff.             2.722E-01                      2.504E-01

----------------------------------------------------------------------------------

                              Thrust Identity                Torque Identity

Advance Coefficient             -0.0542                      0.0834
Thrust Coefficient               3.009E-01                   2.572E-01
Torque Coefficient               3.604E-02                   3.109E-02
Advance Velocity,fps            -1.37                        2.11
Effective Wake                   1.249E+00                   6.172E-01
Open Prop Eff.                  -7.205E-02                   1.102E-01
Relative Rotative Eff            1.159E+00                   1.170E+00
Hull Efficiency (Res. Form 1)   -3.260E+00                   2.118E+00
Hull Efficiency (Res. Form 2)   -2.998E+00                   1.948E+00
```



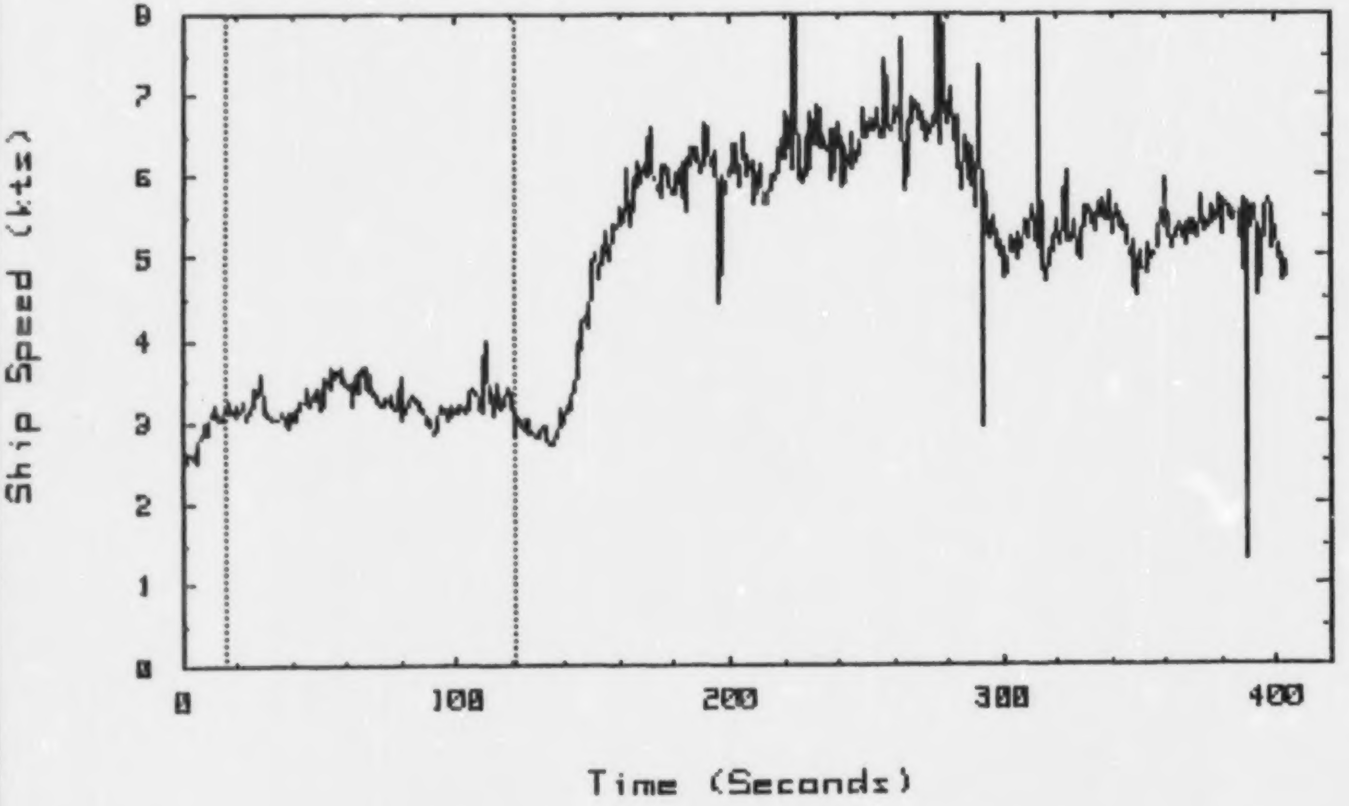
SELF PROPELLED TESTS
SP 6



SELF PROPELLED TESTS
SP 6

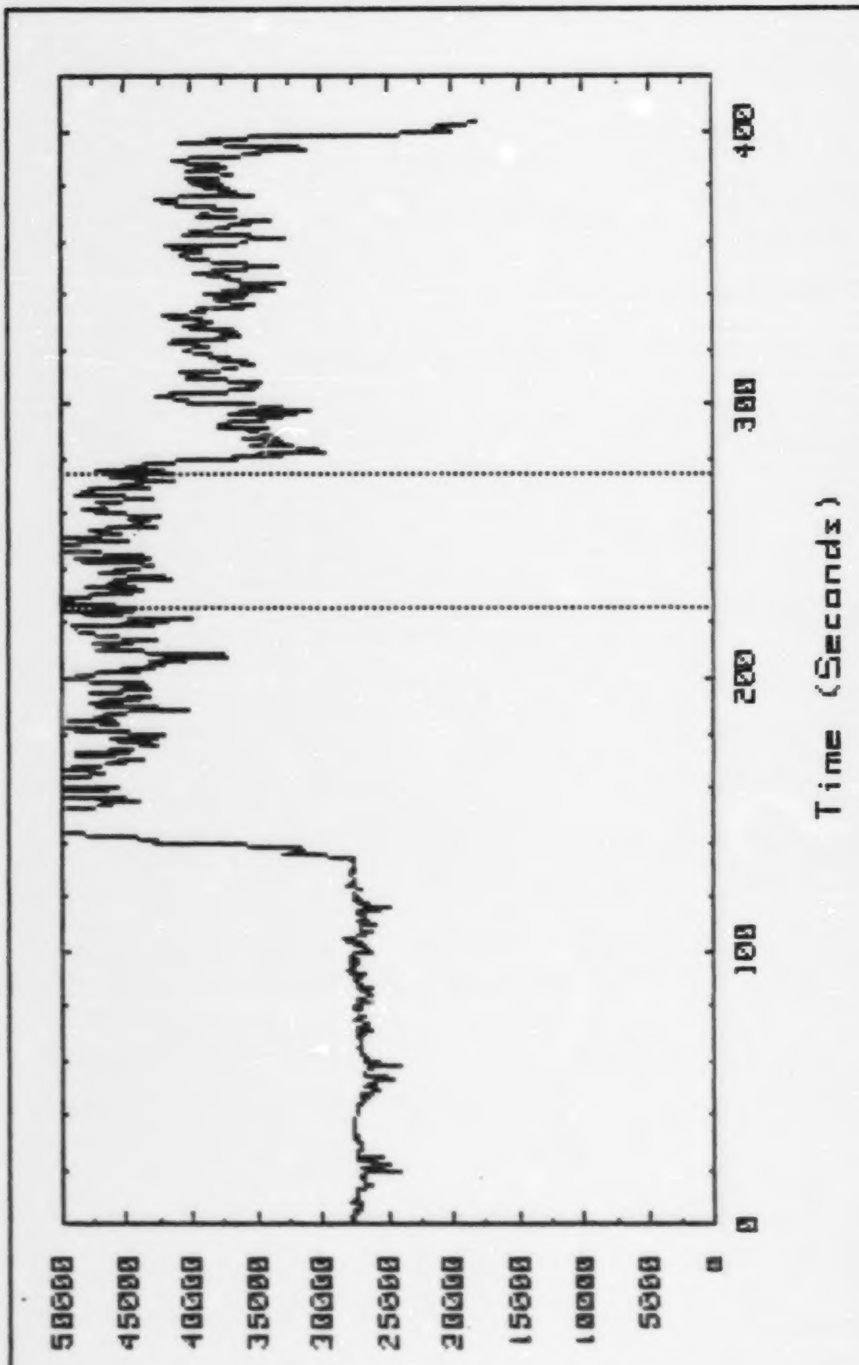


SELF PROPELLED TESTS
SP 6

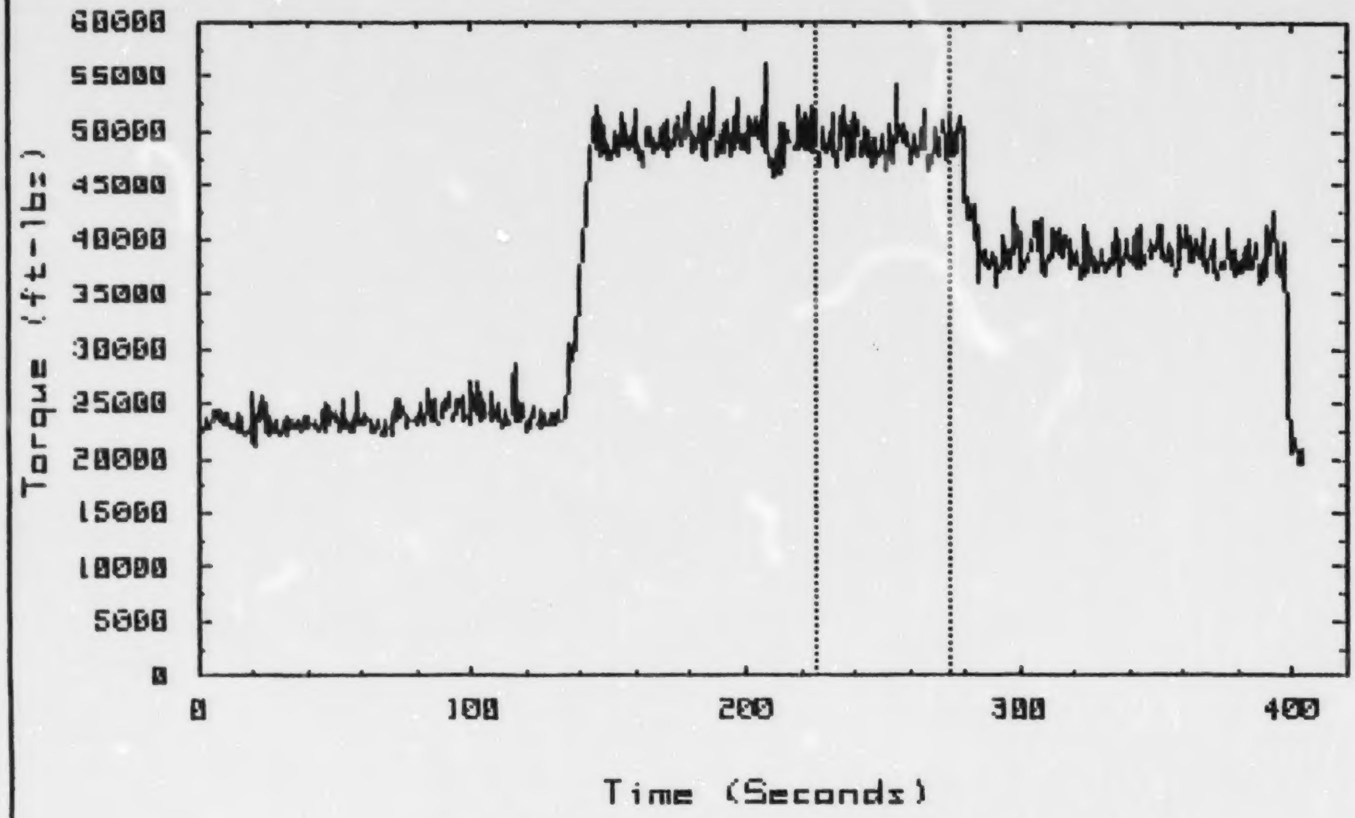


SELF PROPELLED TESTS
SP 6

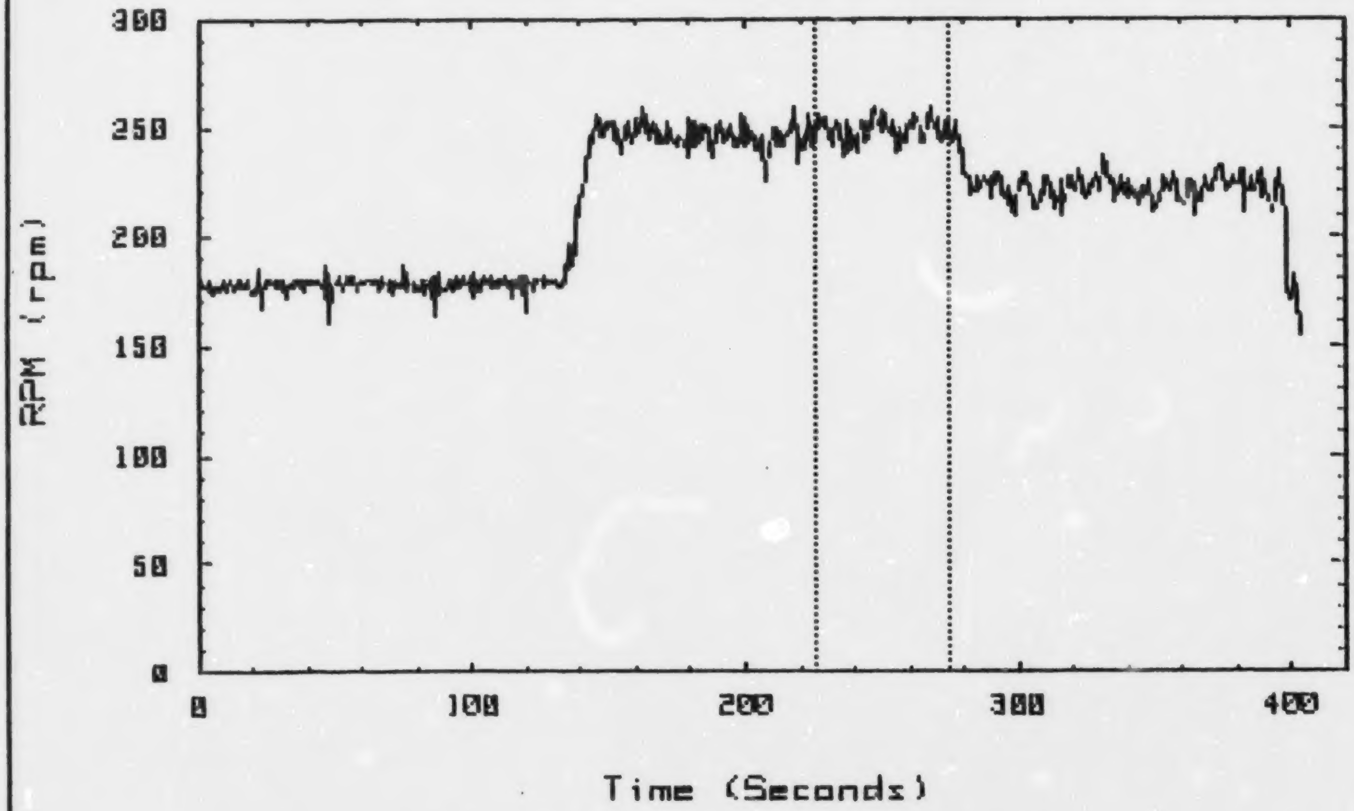
```
           Test Results for Test SP_6B:  02/23/86, 13:54:43
           For the Interval Between  226  sec and  275  sec

  CHANNEL                             MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                      52085.0     41443.0     46298.4      2255.7
 2  Torque (ft-lbs)                   54156.6     46401.1     49078.1      1321.6
 3  RPM (rpm)                           259.1       237.1       249.7         4.5
 4  Ship Speed (kts)                      7.7         5.8         6.5          .3
 6  Shaft Horsepower                   2469.5      2197.1      2332.8        50.7


           Test Results for Test SP_6B:  02/23/86, 13:54:43
           For the Interval Between  226  sec and  275  sec

          Average Ship Speed                     6.5    kts
          Average Thrust                     46298.4    lbs
          Average Torque                     49078.1    ft-lbs
          Average RPM                          249.7    RPM
          Average Shaft Horsepower            2332.8    HP
          Average Ice Thickness               1.1667    ft
          Mean Advance Coeff., Js             0.3116
          Thrust Coefficient, Kt              2.639E-01
          Torque Coefficient, Kq              3.292E-02

---------------------------------------------------------------------------

                      RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs     3.177E+04                      3.183E+04
Thrust Deduction         3.139E-01                      3.126E-01
Propulsive Coeff.        2.729E-01                      2.734E-01

---------------------------------------------------------------------------

                           Thrust Identity                Torque Identity

Advance Coefficient          0.0629                         0.0308
Thrust Coefficient           2.639E-01                      2.743E-01
Torque Coefficient           3.173E-02                      3.292E-02
Advance Velocity,fps         2.23                           1.09
Effective Wake               7.980E-01                      9.013E-01
Open Prop Eff.               8.331E-02                      4.085E-02
Relative Rotative Eff        9.640E-01                      9.623E-01
Hull Efficiency (Res. Form 1)  3.397E+00                    6.948E+00
Hull Efficiency (Res. Form 2)  3.404E+00                    6.962E+00
```



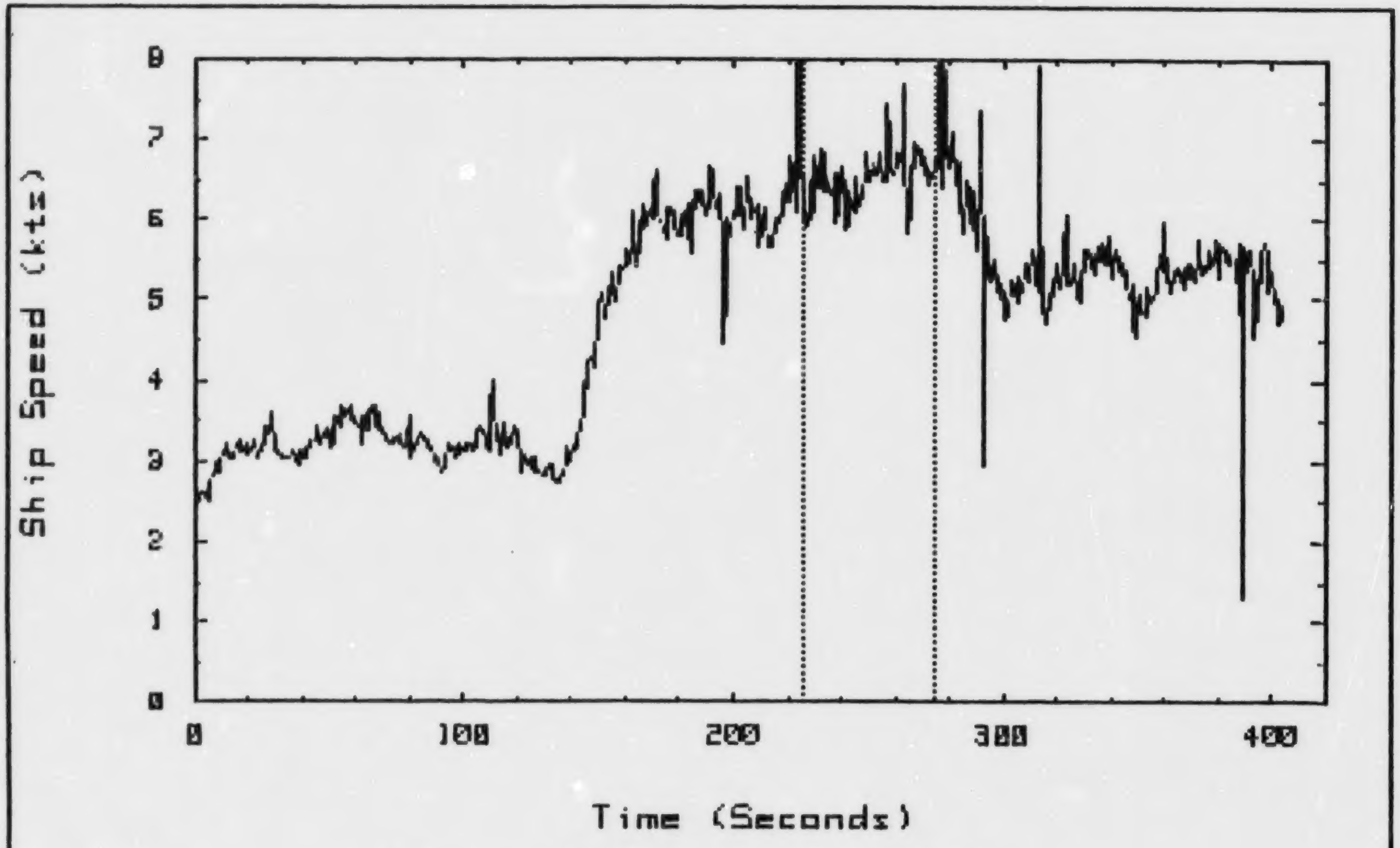
SELF PROPELLED TESTS
SP 6



SELF PROPELLED TESTS
SP 6

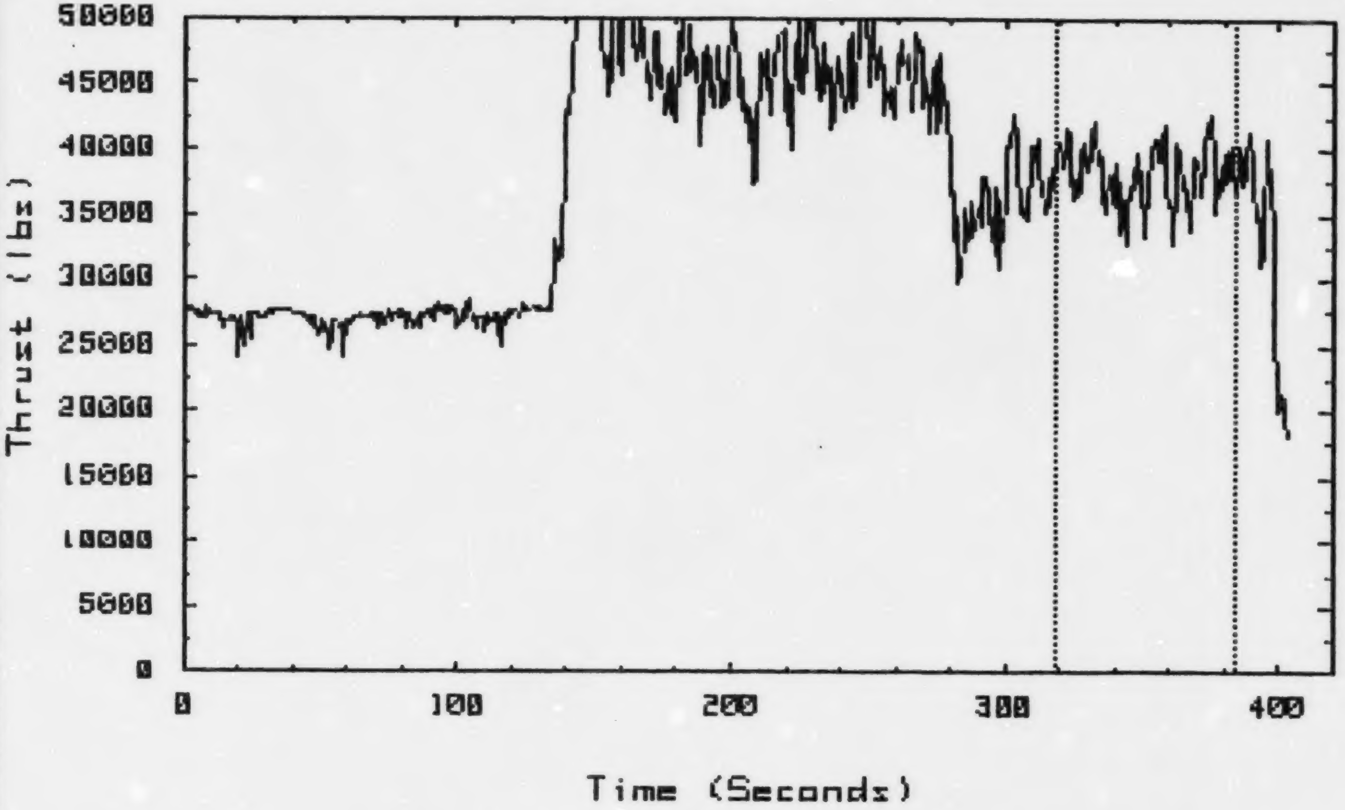


SELF PROPELLED TESTS
SP 6

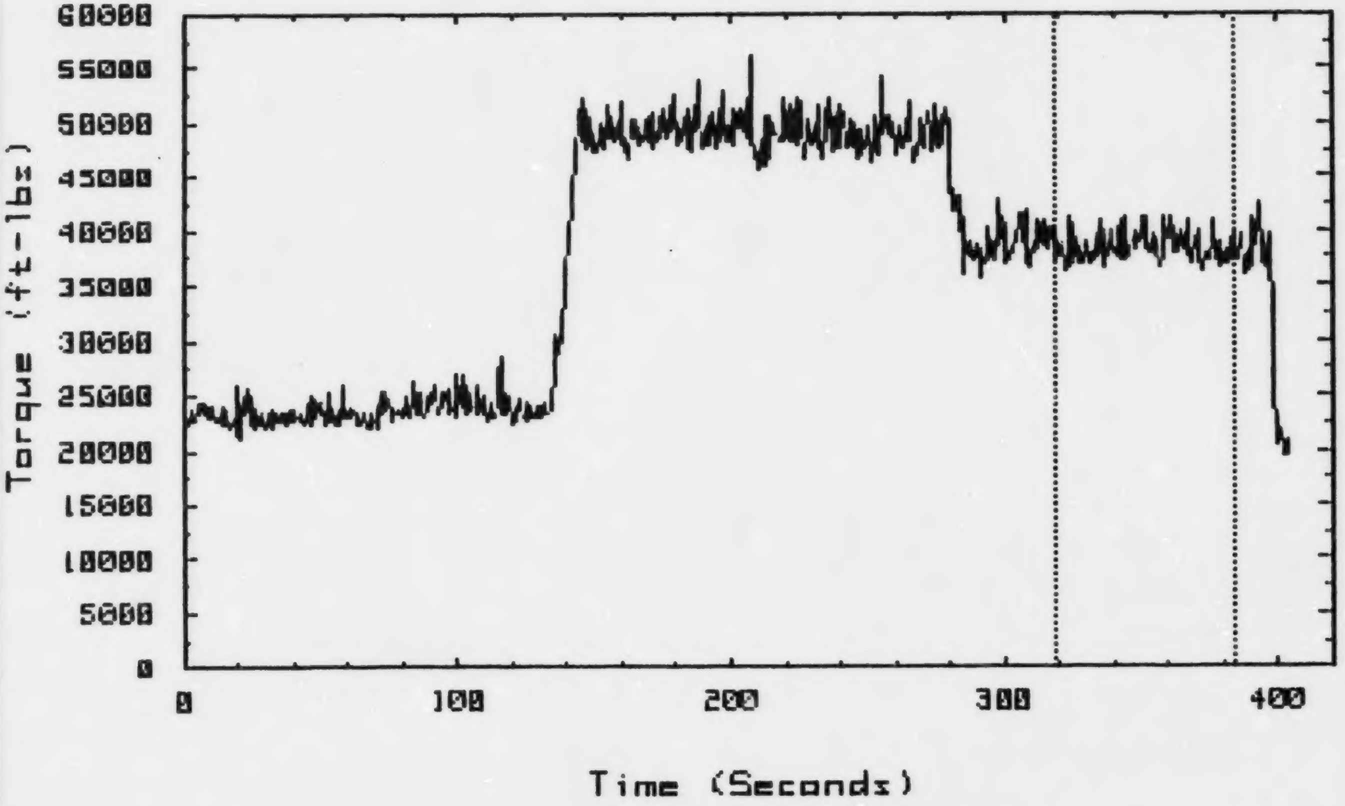


SELF PROPELLED TESTS
SP 6

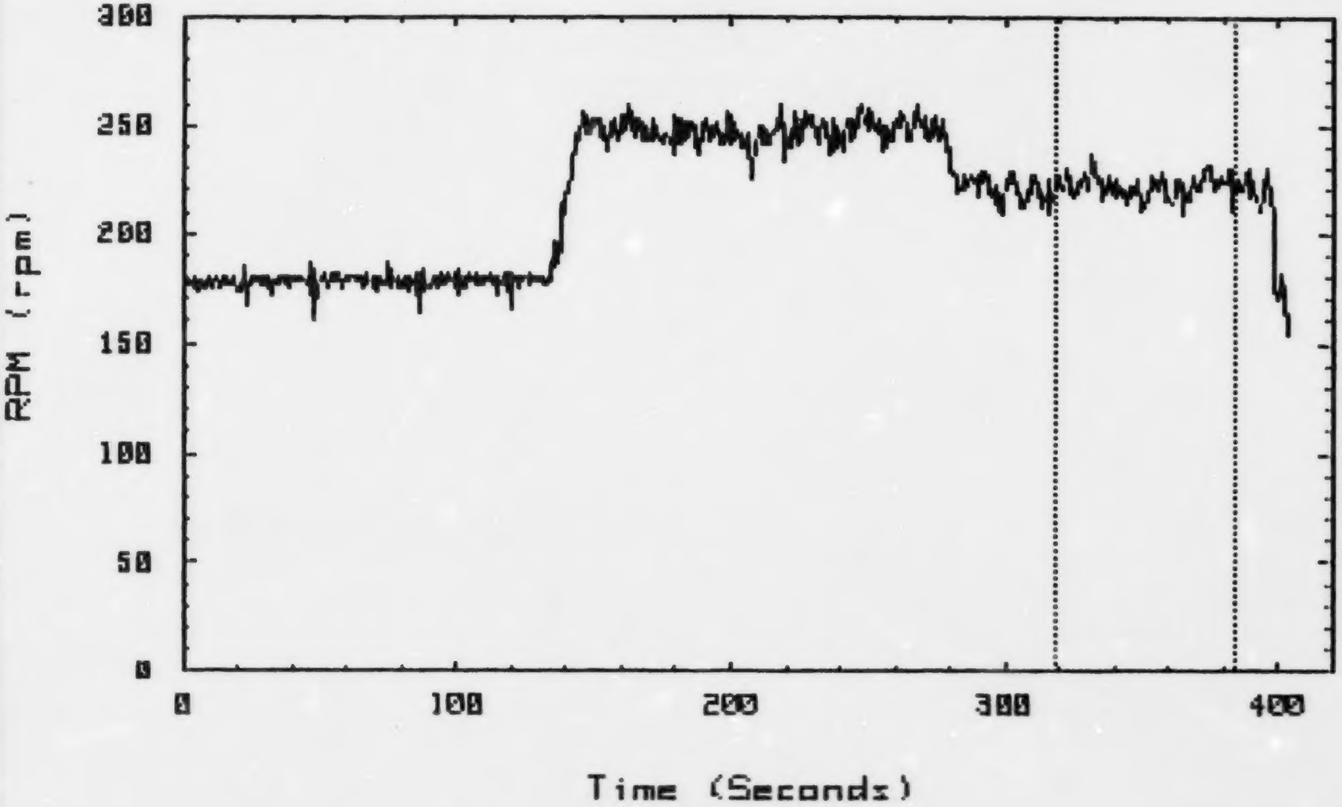
```
         Test Results for Test SP_6C:  02/23/86, 13:54:43
         For the Interval Between  318  sec and  384  sec

 CHANNEL                        MAXIMUM     MINIMUM       MEAN     STDRD DEV

1  Thrust (lbs)                 42672.8     32645.7     38232.5       2074.3
2  Torque (ft-lbs)              41346.6     36318.9     38599.3       1075.7
3  RPM (rpm)                      236.9       209.2       222.7          4.4
4  Ship Speed (kts)                 6.1         4.6         5.4           .2
6  Shaft Horsepower              1748.6      1541.4      1636.4         36.0


         Test Results for Test SP_6C:  02/23/86, 13:54:43
         For the Interval Between  318  sec and  384  sec

        Average Ship Speed                 5.4   kts
        Average Thrust                 38232.5   lbs
        Average Torque                 38599.3   ft-lbs
        Average RPM                      222.7   RPM
        Average Shaft Horsepower        1636.4   HP
        Average Ice Thickness           1.0833   ft
        Mean Advance Coeff., Js         0.2865
        Thrust Coefficient, Kt          2.739E-01
        Torque Coefficient, Kq          3.254E-02

--------------------------------------------------------------------------------

                          RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs          2.481E+04                       2.487E+04
Thrust Deduction              3.510E-01                       3.496E-01
Propulsive Coeff.             2.491E-01                       2.497E-01

--------------------------------------------------------------------------------

                            Thrust Identity                 Torque Identity

Advance Coefficient           0.0319                          0.0416
Thrust Coefficient            2.739E-01                       2.708E-01
Torque Coefficient            3.284E-02                       3.254E-02
Advance Velocity,fps          1.01                            1.31
Effective Wake                8.888E-01                       8.547E-01
Open Prop Eff.                4.230E-02                       5.523E-02
Relative Rotative Eff         1.009E+00                       1.012E+00
Hull Efficiency (Res. Form 1) 5.834E+00                       4.466E+00
Hull Efficiency (Res. Form 2) 5.847E+00                       4.476E+00
```



SELF PROPELLED TESTS
SP 6



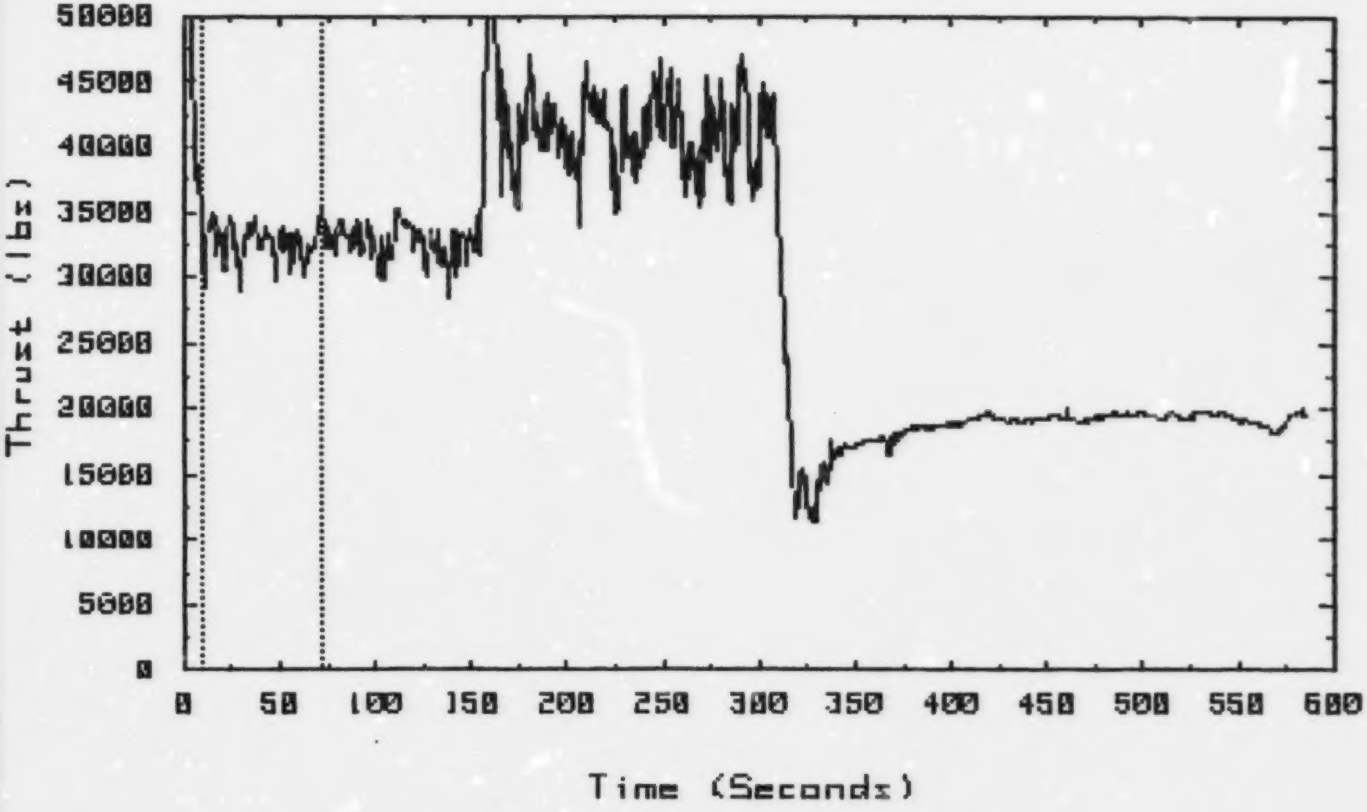
SELF PROPELLED TESTS
SP 6



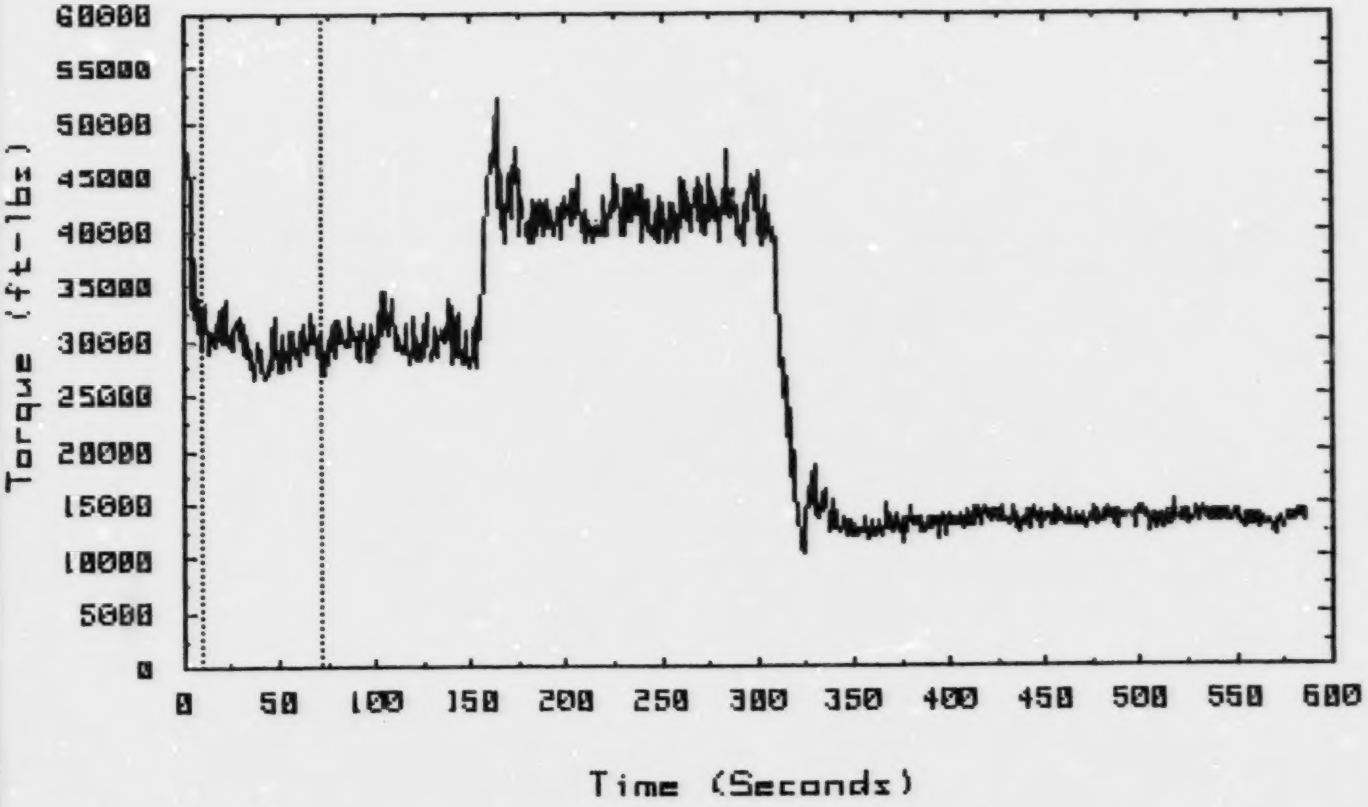
SELF PROPELLED TESTS
SP 6

```
               Test Results for Test SP_7A:  02/23/86, 14:11:53
               For the Interval Between  10  sec and  72  sec

  CHANNEL                              MAXIMUM      MINIMUM       MEAN       STDRD DEV

 1  Thrust (lbs)                       35080.4      29026.3      32741.6       1155.1
 2  Torque (ft-lbs)                    33799.9      26632.7      29873.8       1513.0
 3  RPM (rpm)                            216.0        195.0        204.3          3.0
 4  Ship Speed (kts)                       5.6          4.2          4.9           .2
 6  Shaft Horsepower                    1323.3       1035.2       1161.6         57.2
```

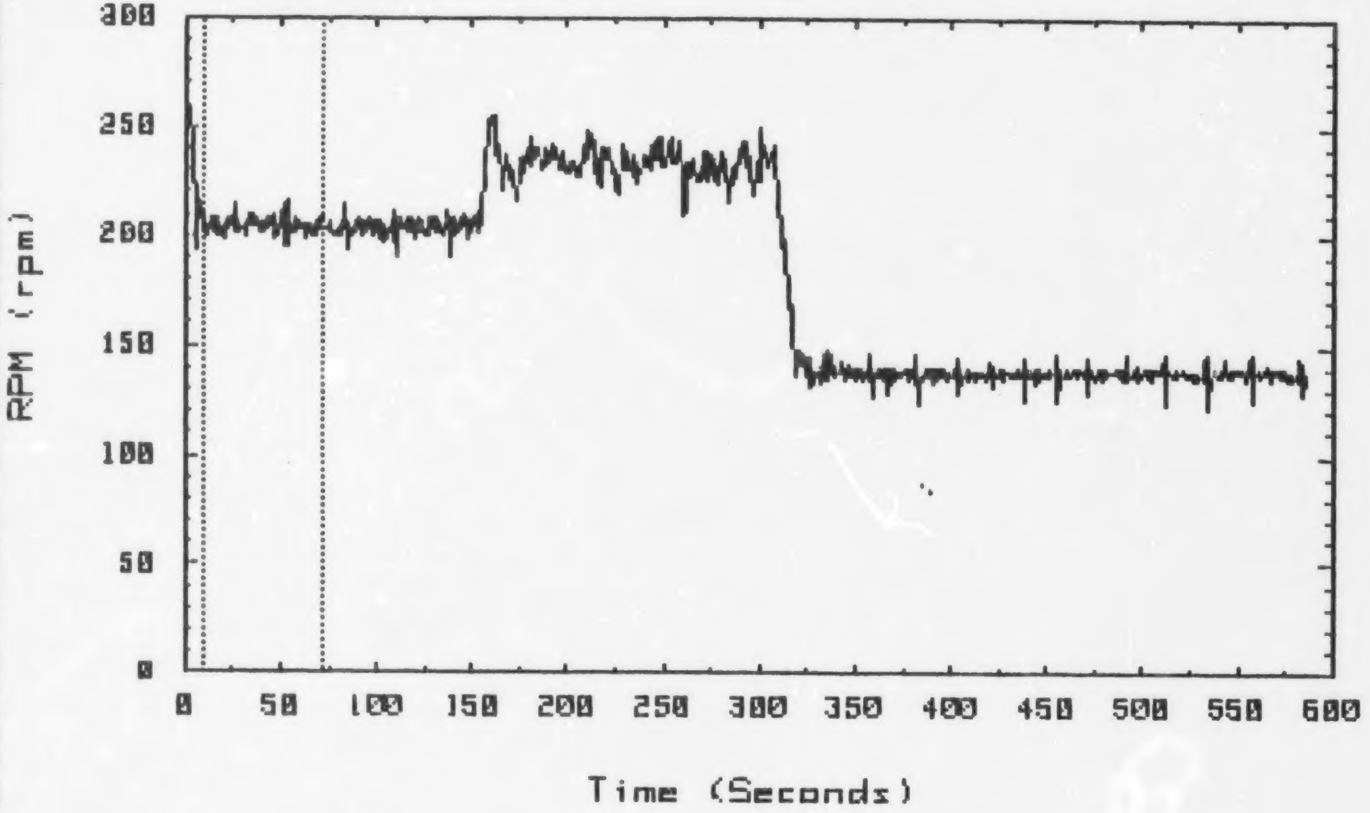
```
               Test Results for Test SP_7A:  02/23/86, 14:11:53
               For the Interval Between  10  sec and  72  sec

              Average Ship Speed                  4.9   kts
              Average Thrust                  32741.6   lbs
              Average Torque                  29873.8   ft-lbs
              Average RPM                       204.3   RPM
              Average Shaft Horsepower         1161.6   HP
              Average Ice Thickness            1.1250   ft
              Mean Advance Coeff., Js          0.2842
              Thrust Coefficient, Kt         2.790E-01
              Torque Coefficient, Kq         2.995E-02

-------------------------------------------------------------------------------

                         RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs         2.413E+04                       2.286E+04
Thrust Deduction             2.631E-01                       3.019E-01
Propulsive Coeff.            3.105E-01                       2.941E-01

-------------------------------------------------------------------------------

                           Thrust Identity                 Torque Identity

Advance Coefficient          0.0161                          0.1166
Thrust Coefficient           2.790E-01                       2.463E-01
Torque Coefficient           3.341E-02                       2.995E-02
Advance Velocity,fps          .47                            3.37
Effective Wake               9.434E-01                       5.899E-01
Open Prop Eff.               2.139E-02                       1.530E-01
Relative Rotative Eff        1.116E+00                       1.133E+00
Hull Efficiency (Res. Form 1)  1.301E+01                     1.797E+00
Hull Efficiency (Res. Form 2)  1.232E+01                     1.702E+00
```



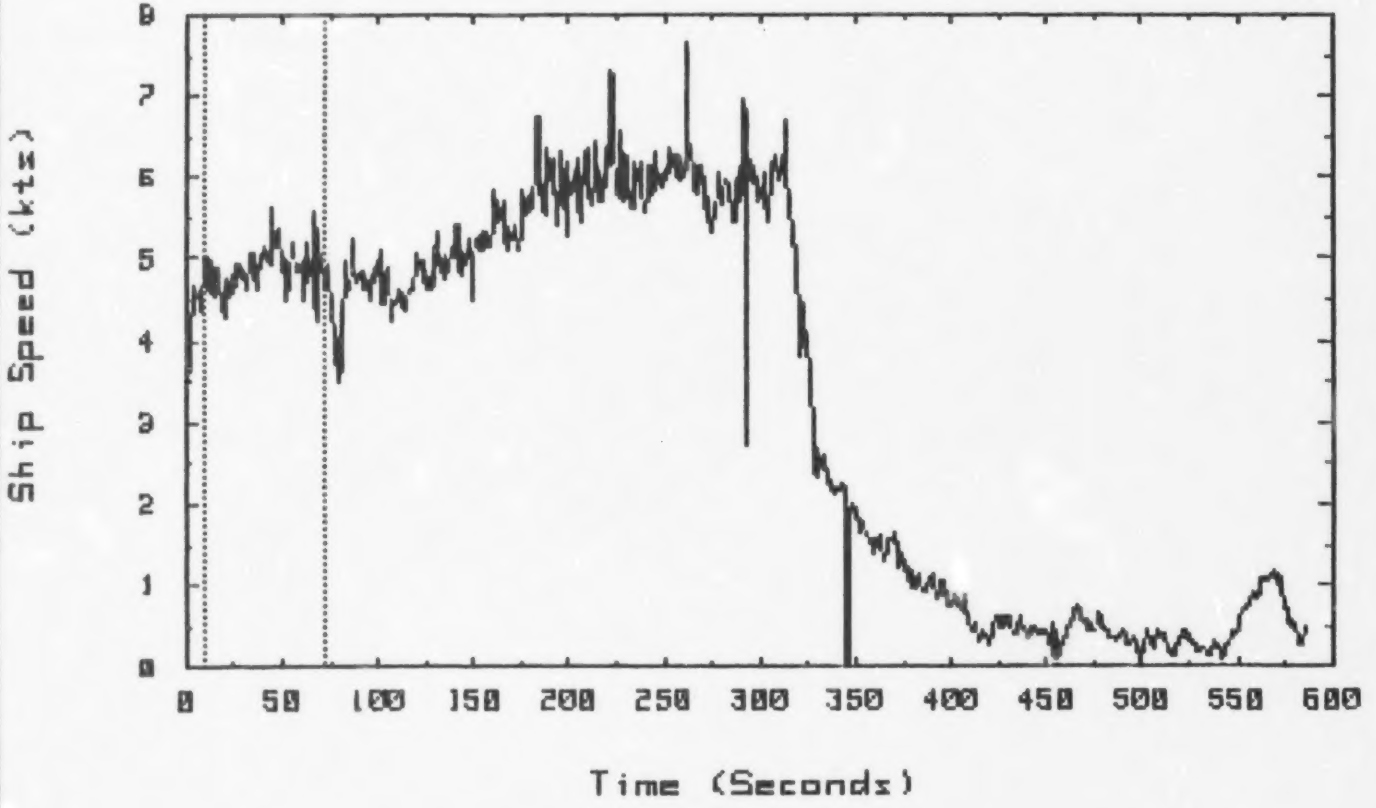
SELF PROPELLED TESTS
SP 7



SELF PROPELLED TESTS
SP 7

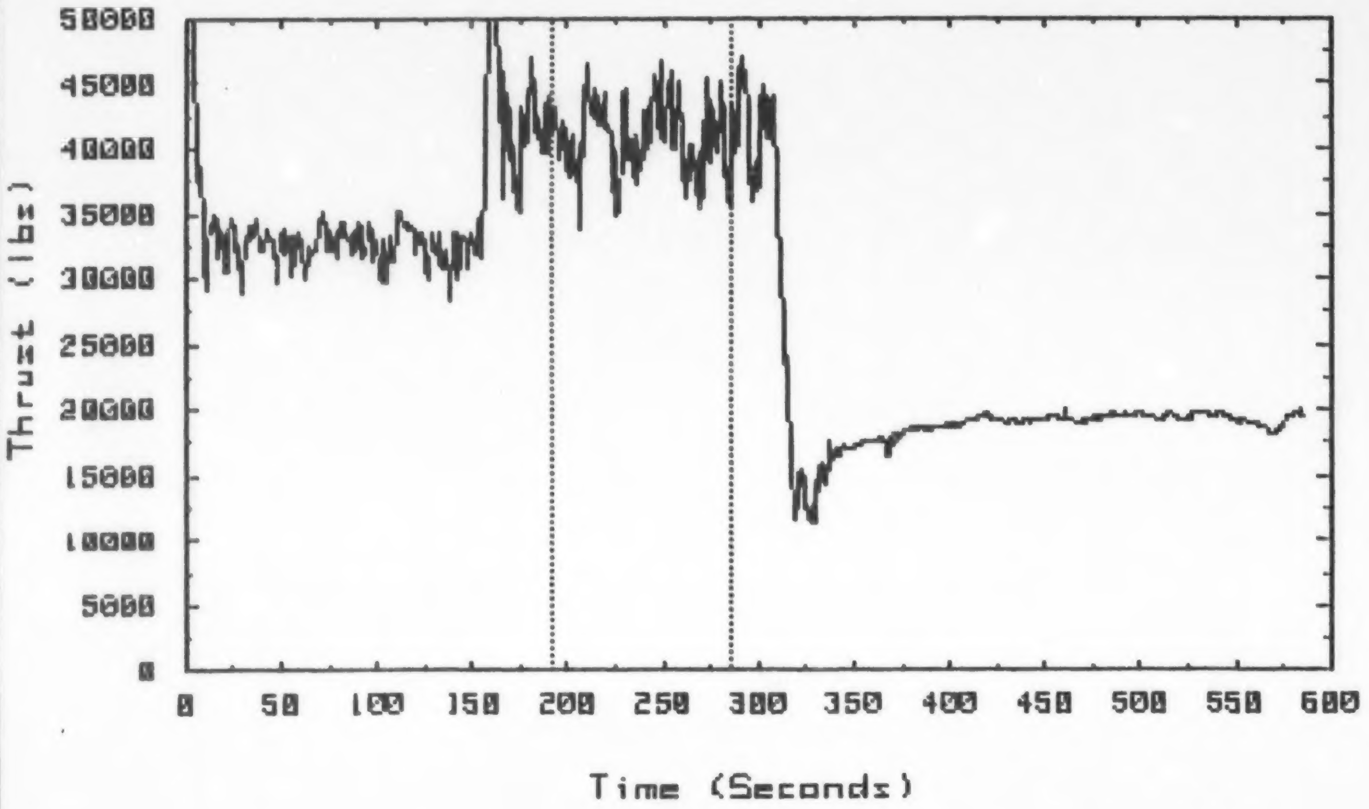


SELF PROPELLED TESTS
SP 7

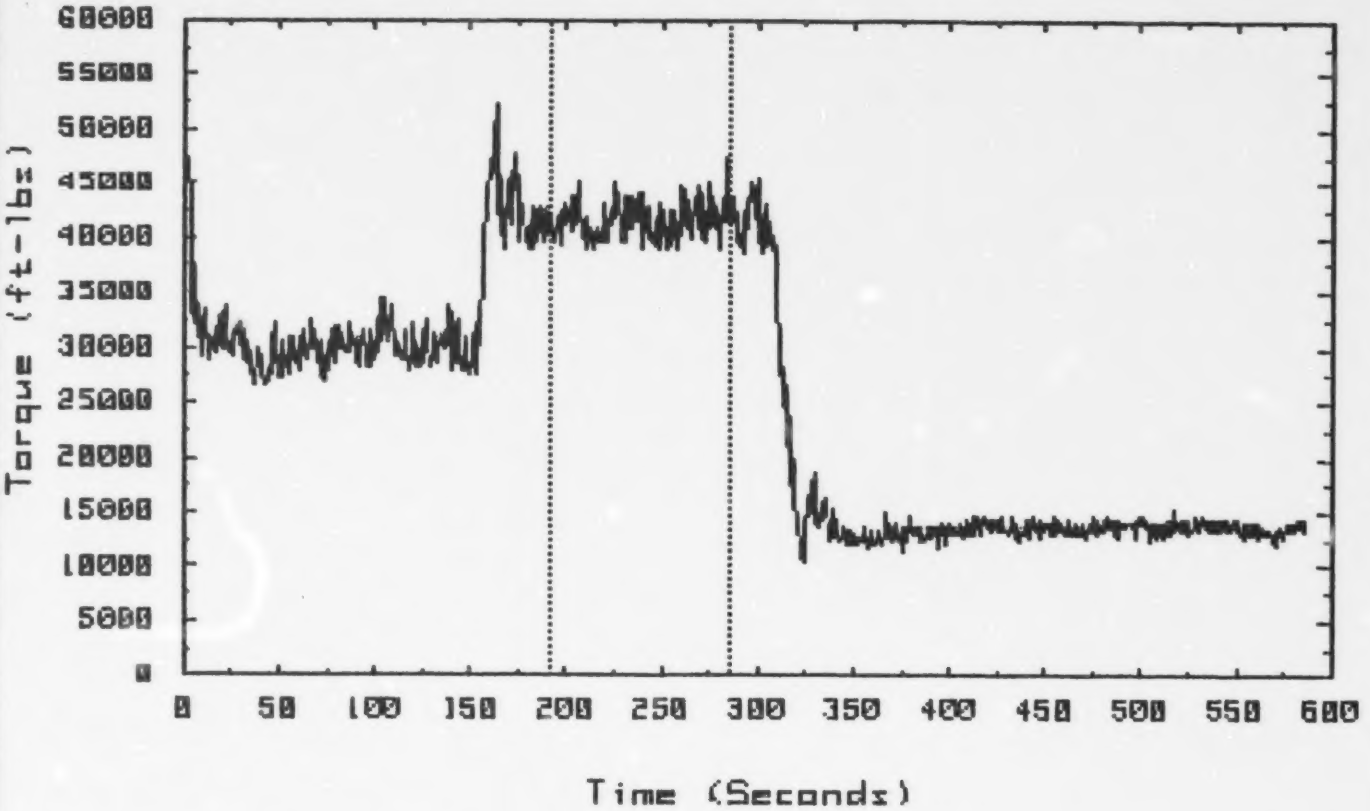


SELF PROPELLED TESTS
SP 7

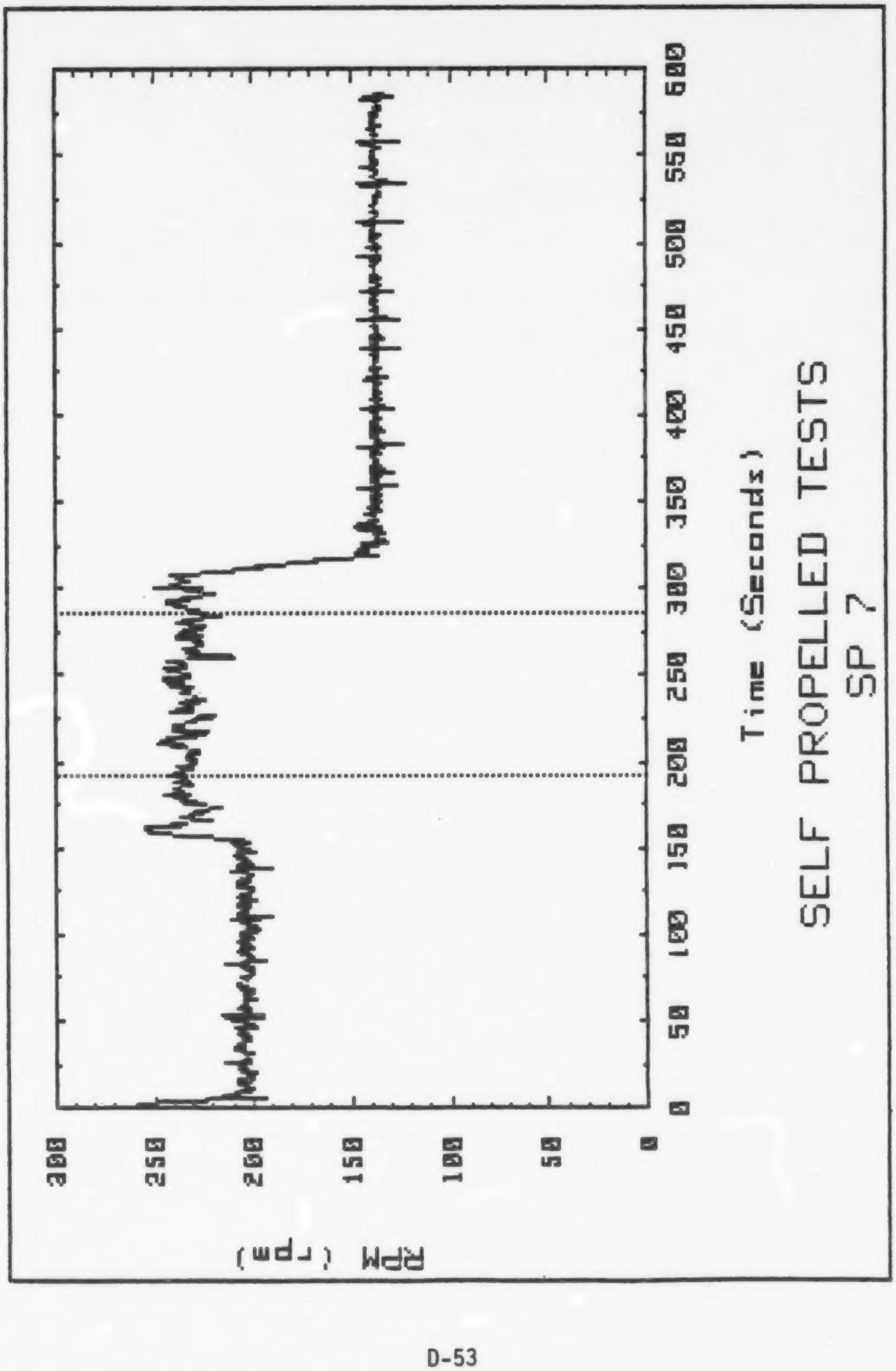
```
              Test Results for Test SP_7B:  02/23/86, 14:11:53
              For the Interval Between  191  sec and  286  sec

   CHANNEL                            MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                      46715.6     33898.0     40982.8      2534.8
 2  Torque (ft-lbs)                   47224.9     38800.8     41589.6      1451.3
 3  RPM (rpm)                           247.7       208.8       233.6         5.7
 4  Ship Speed (kts)                      7.7         5.3         6.0          .3
 6  Shaft Horsepower                   2001.6      1698.1      1848.7        47.3


              Test Results for Test SP_7B:  02/23/86, 14:11:53
              For the Interval Between  191  sec and  286  sec

             Average Ship Speed                   6.0   kts
             Average Thrust                   40982.8   lbs
             Average Torque                   41589.6   ft-lbs
             Average RPM                        233.6   RPM
             Average Shaft Horsepower          1848.7   HP
             Average Ice Thickness             1.0275   ft
             Mean Advance Coeff., Js           0.3064
             Thrust Coefficient, Kt            2.670E-01
             Torque Coefficient, Kq            3.187E-02

--------------------------------------------------------------------------------

                          RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs          2.564E+04                      2.854E+04
Thrust Deduction              3.745E-01                      3.035E-01
Propulsive Coeff.             2.555E-01                      2.845E-01

--------------------------------------------------------------------------------

                           Thrust Identity                 Torque Identity

Advance Coefficient           0.0535                         0.0608
Thrust Coefficient            2.670E-01                      2.646E-01
Torque Coefficient            3.206E-02                      3.187E-02
Advance Velocity,fps          1.77                           2.01
Effective Wake                8.253E-01                      8.016E-01
Open Prop Eff.                7.094E-02                      8.047E-02
Relative Rotative Eff         1.006E+00                      1.009E+00
Hull Efficiency (Res. Form 1) 3.580E+00                      3.153E+00
Hull Efficiency (Res. Form 2) 3.986E+00                      3.511E+00
```



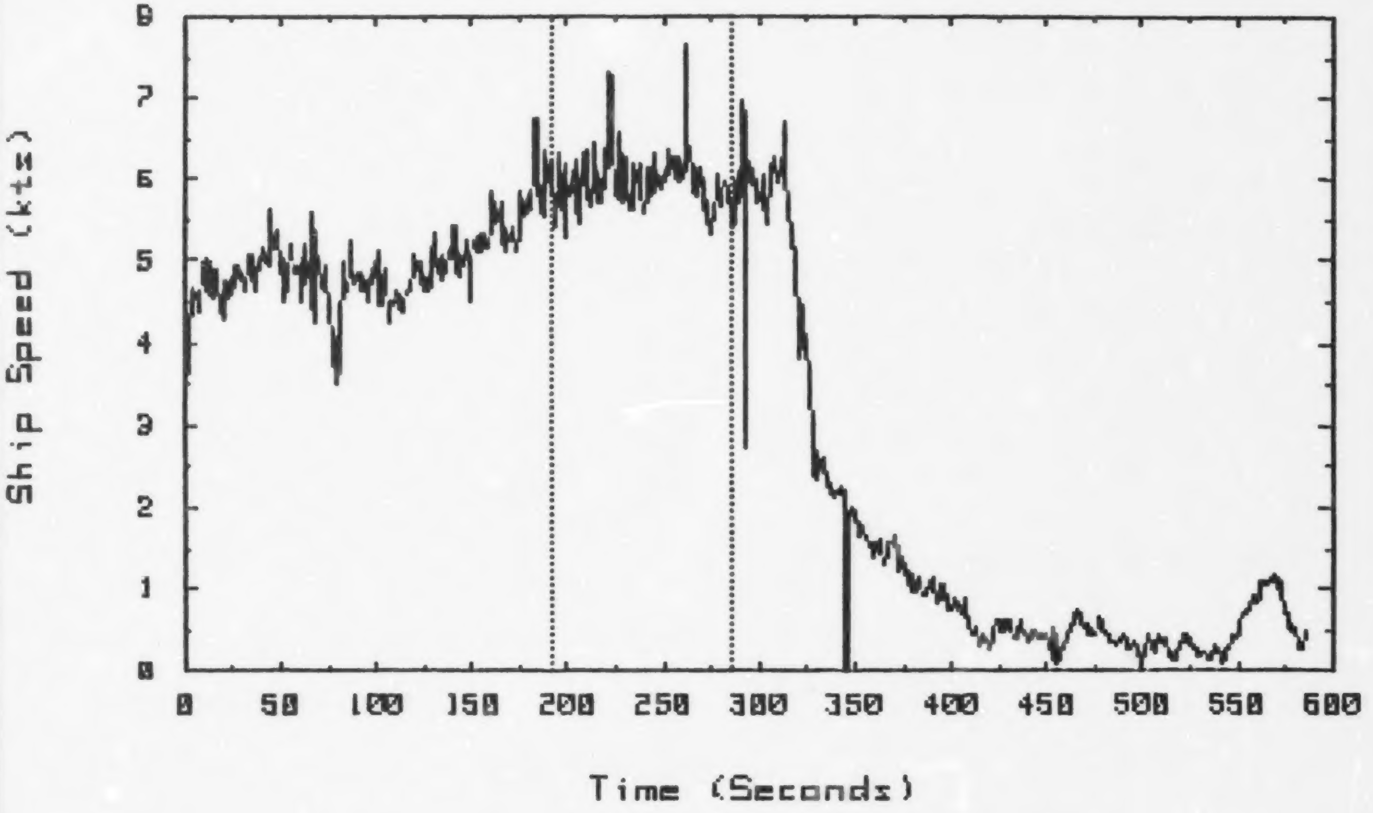
SELF PROPELLED TESTS
SP 7



SELF PROPELLED TESTS
SP 7

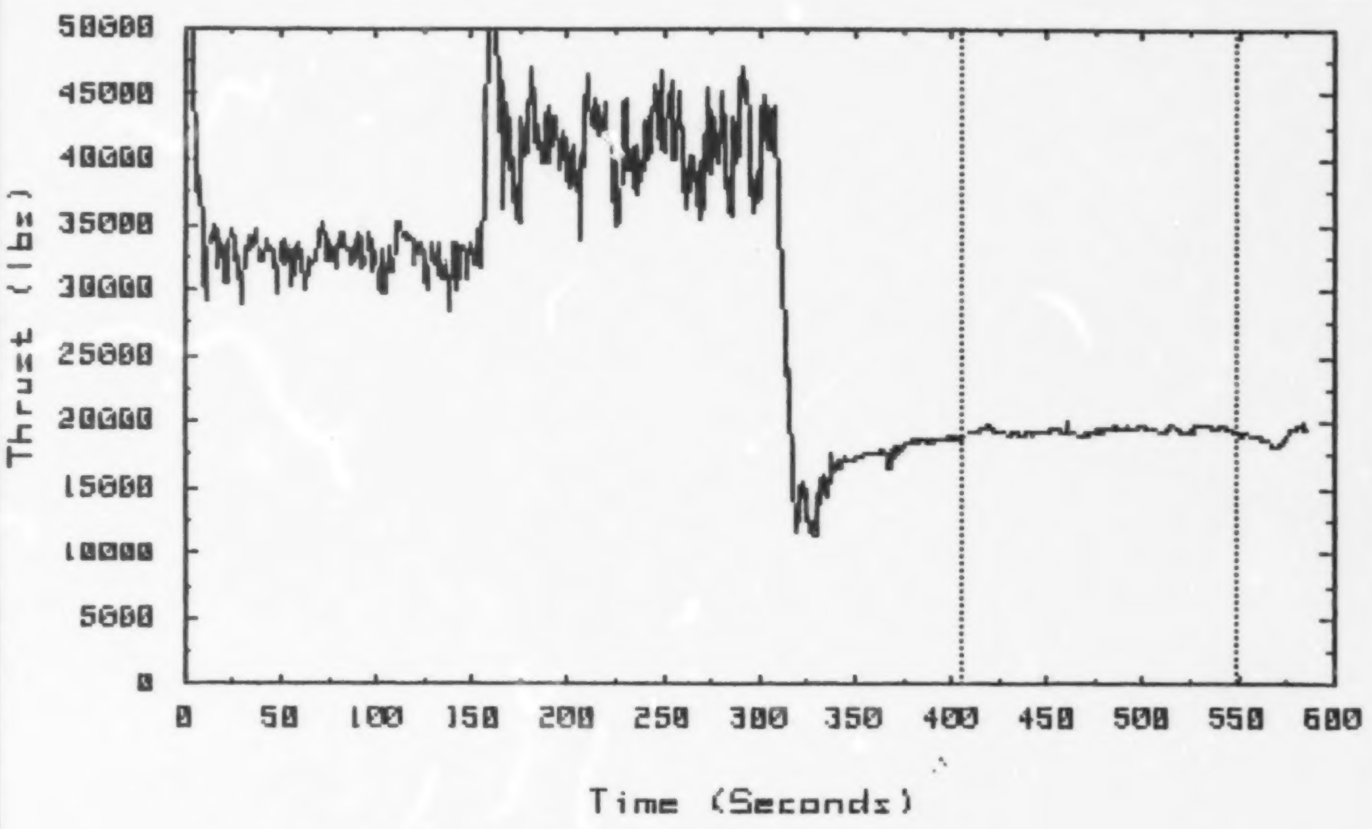


SELF PROPELLED TESTS
SP 7

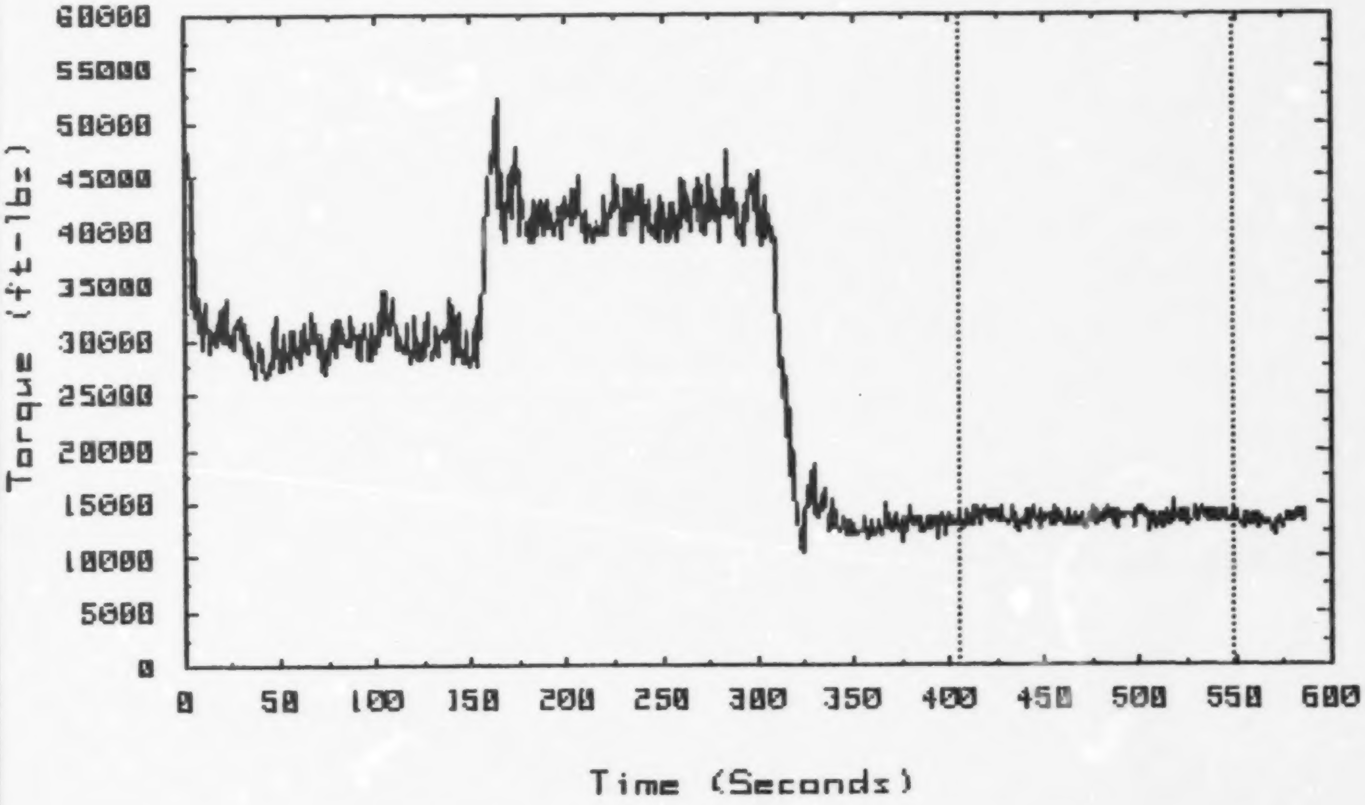


SELF PROPELLED TESTS
SP 7

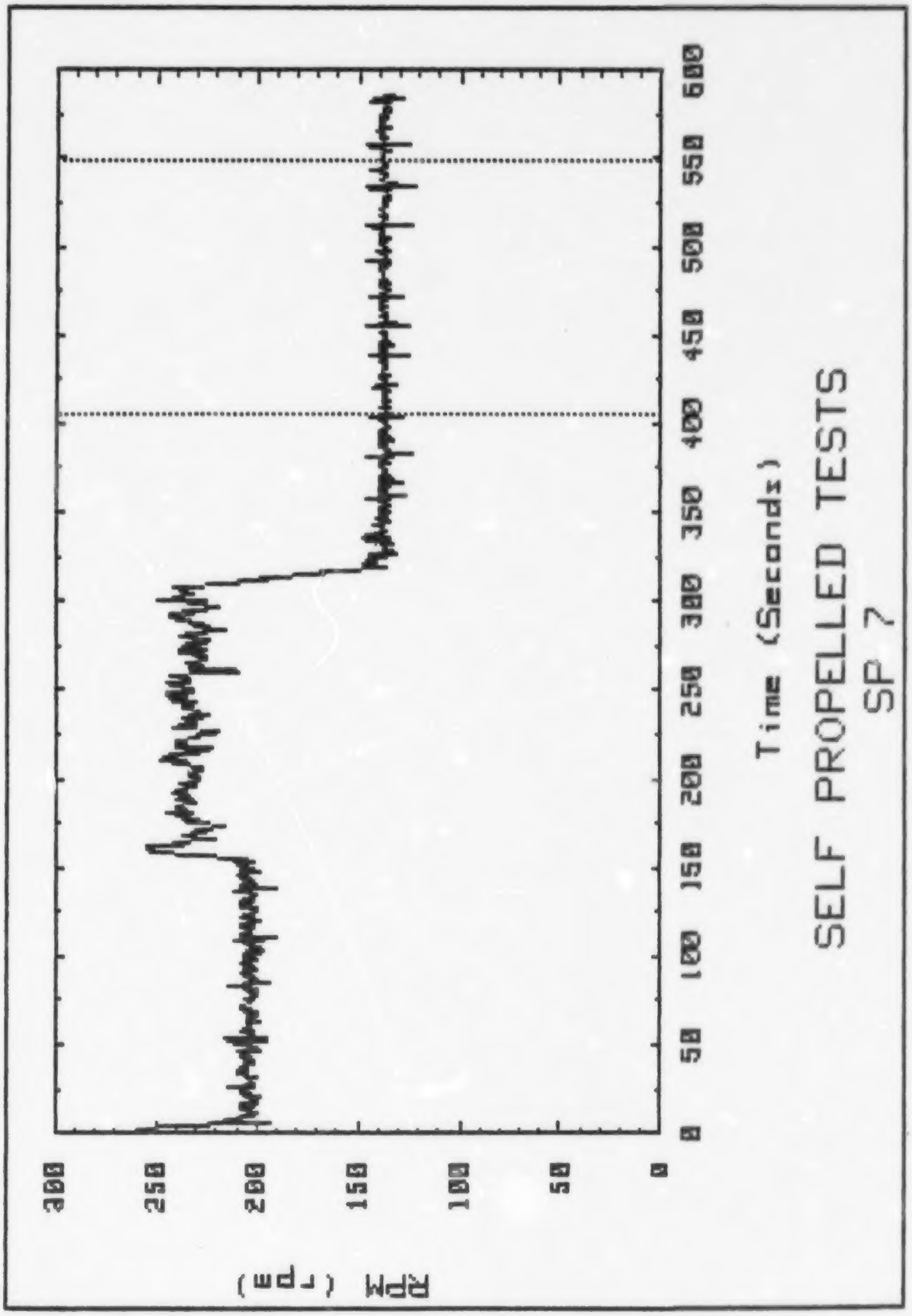
```
                Test Results for Test SP_7C:  02/23/86, 14:11:53
                For the Interval Between  405  sec and  549  sec

  CHANNEL                              MAXIMUM     MINIMUM      MEAN      STDRD DEV

1  Thrust (lbs)                        19992.5     18810.1     19384.7      231.7
2  Torque (ft-lbs)                     15159.9     12405.3     13773.9      418.6
3  RPM (rpm)                             146.2       121.5       138.0        2.4
4  Ship Speed (kts)                         .9          .1          .4         .1
6  Shaft Horsepower                      402.8       306.7       361.9       13.1


                Test Results for Test SP_7C:  02/23/86, 14:11:53
                For the Interval Between  405  sec and  549  sec

               Average Ship Speed                      .4   kts
               Average Thrust                     19384.7   lbs
               Average Torque                     13773.9   ft-lbs
               Average RPM                          138.0   RPM
               Average Shaft Horsepower             361.9   HP
               Average Ice Thickness               1.2917   ft
               Mean Advance Coeff., Js             0.0341
               Thrust Coefficient, Kt             3.620E-01
               Torque Coefficient, Kq             3.026E-02

-------------------------------------------------------------------------------

                      RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs      9.809E+03                       1.595E+04
Thrust Deduction          4.940E-01                       1.773E-01
Propulsive Coeff.         3.286E-02                       5.342E-02

-------------------------------------------------------------------------------

                        Thrust Identity                Torque Identity

Advance Coefficient       -0.2637                        0.1074
Thrust Coefficient         3.620E-01                     2.493E-01
Torque Coefficient         4.514E-02                     3.026E-02
Advance Velocity,fps      -5.16                          2.10
Effective Wake             8.732E+00                    -2.150E+00
Open Prop Eff.            -3.372E-01                     1.413E-01
Relative Rotative Eff      1.492E+00                     1.452E+00
Hull Efficiency (Res. Form 1)  -6.544E-02                1.606E-01
Hull Efficiency (Res. Form 2)  -1.064E-01                2.612E-01
```



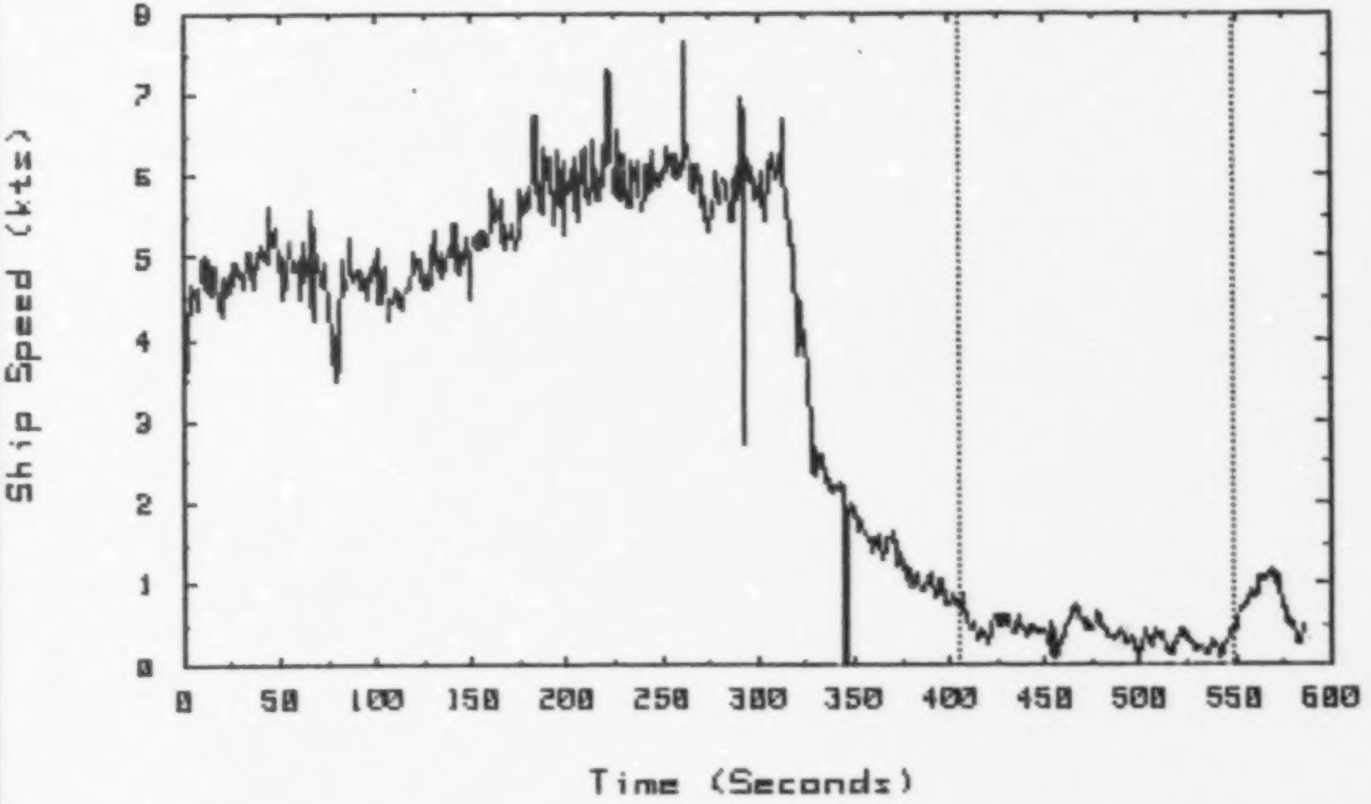
SELF PROPELLED TESTS
SP 7



SELF PROPELLED TESTS
SP 7



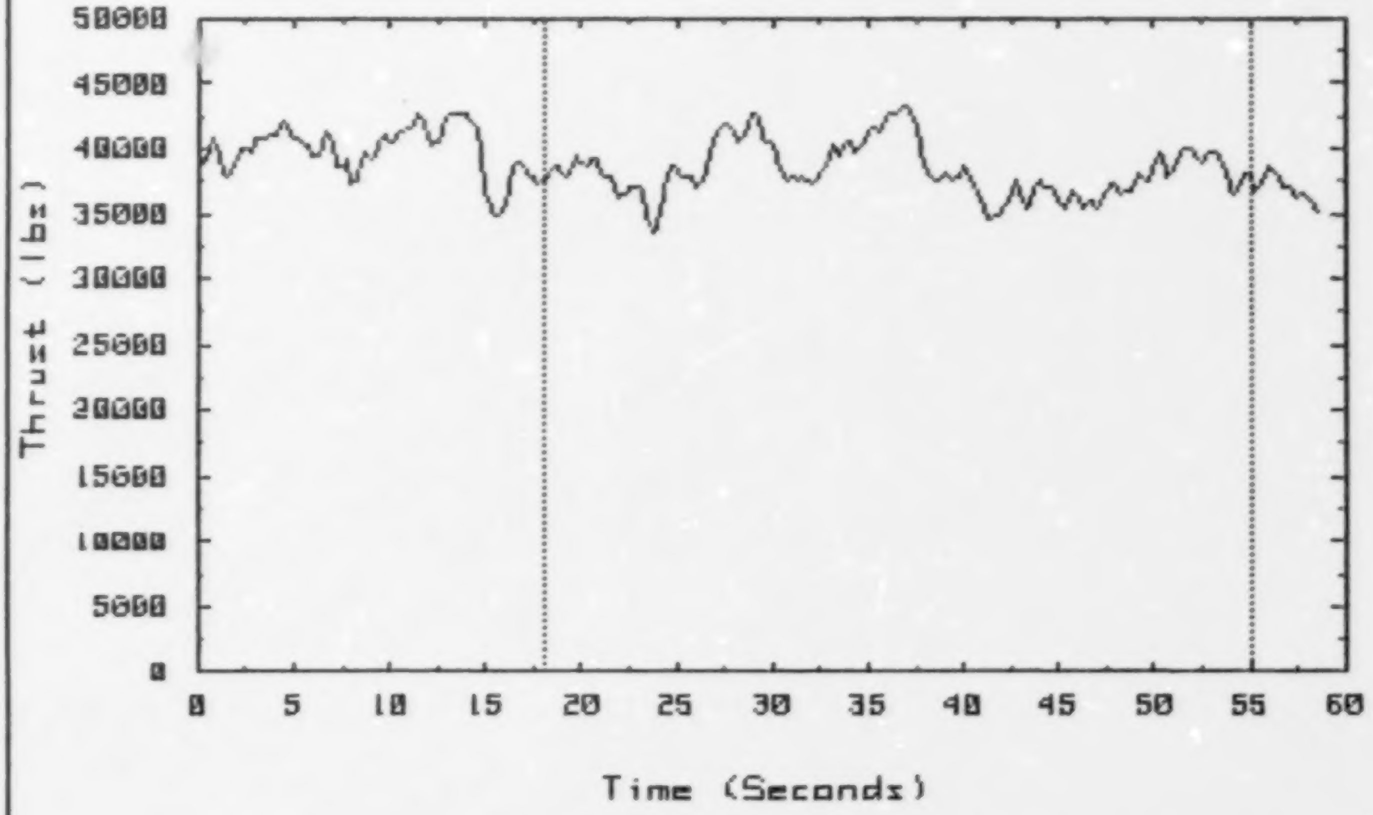
SELF PROPELLED TESTS
SP 7



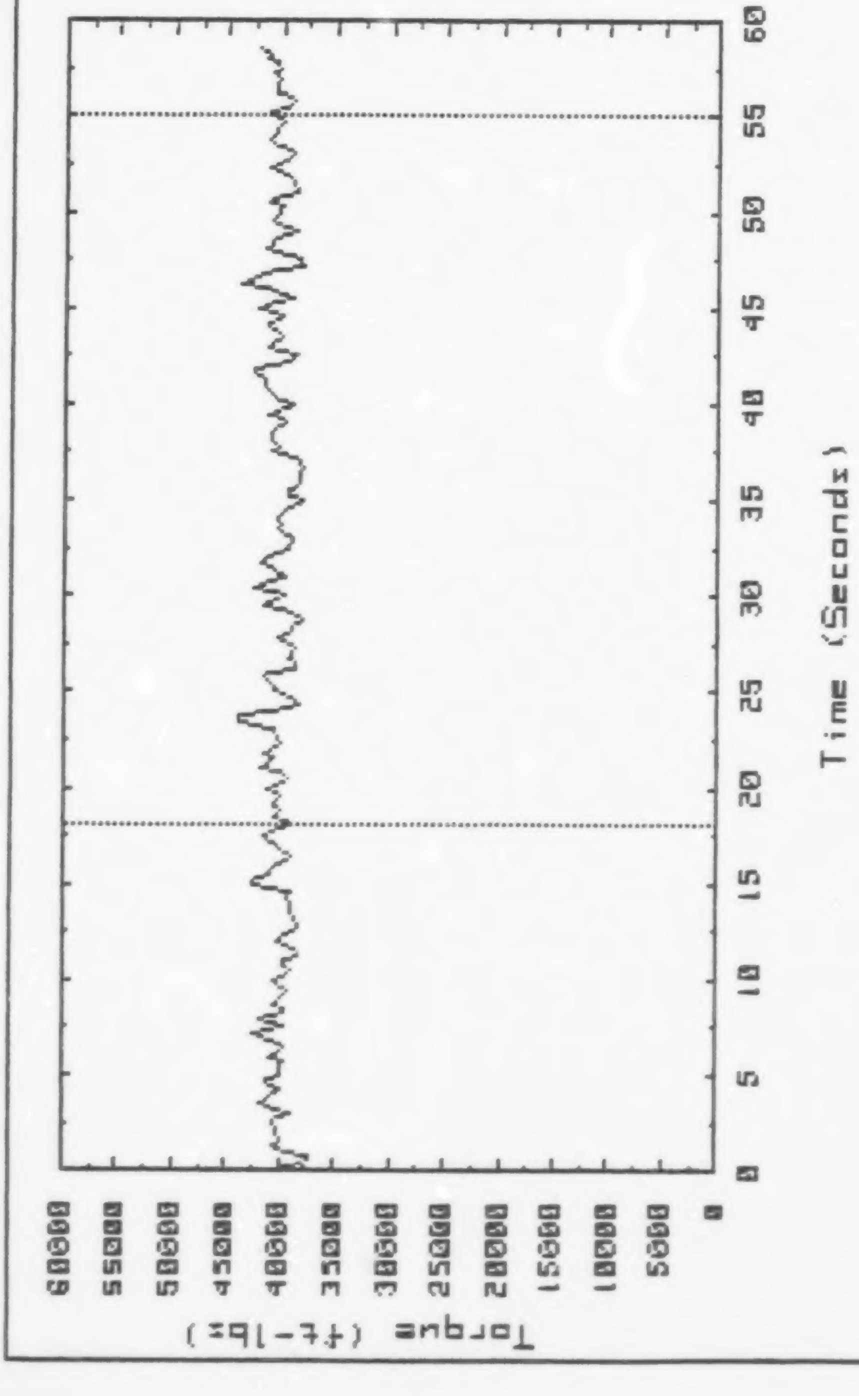
SELF PROPELLED TESTS
SP 7

```
              Test Results for Test SP_8:  02/23/86, 15:45:09
              For the Interval Between  18  sec and  55  sec

   CHANNEL                             MAXIMUM    MINIMUM      MEAN    STDRD DEV

 1  Thrust (lbs)                       43238.1    33494.8    38350.0      2031.5
 2  Torque (ft-lbs)                    43859.6    37976.1    40206.5      1198.2
 3  RPM (rpm)                            234.0      188.7      218.9         5.0
 4  Ship Speed (kts)                       6.0        4.6        5.2          .2
 6  Shaft Horsepower                    1813.4     1364.4     1675.6        50.8
```

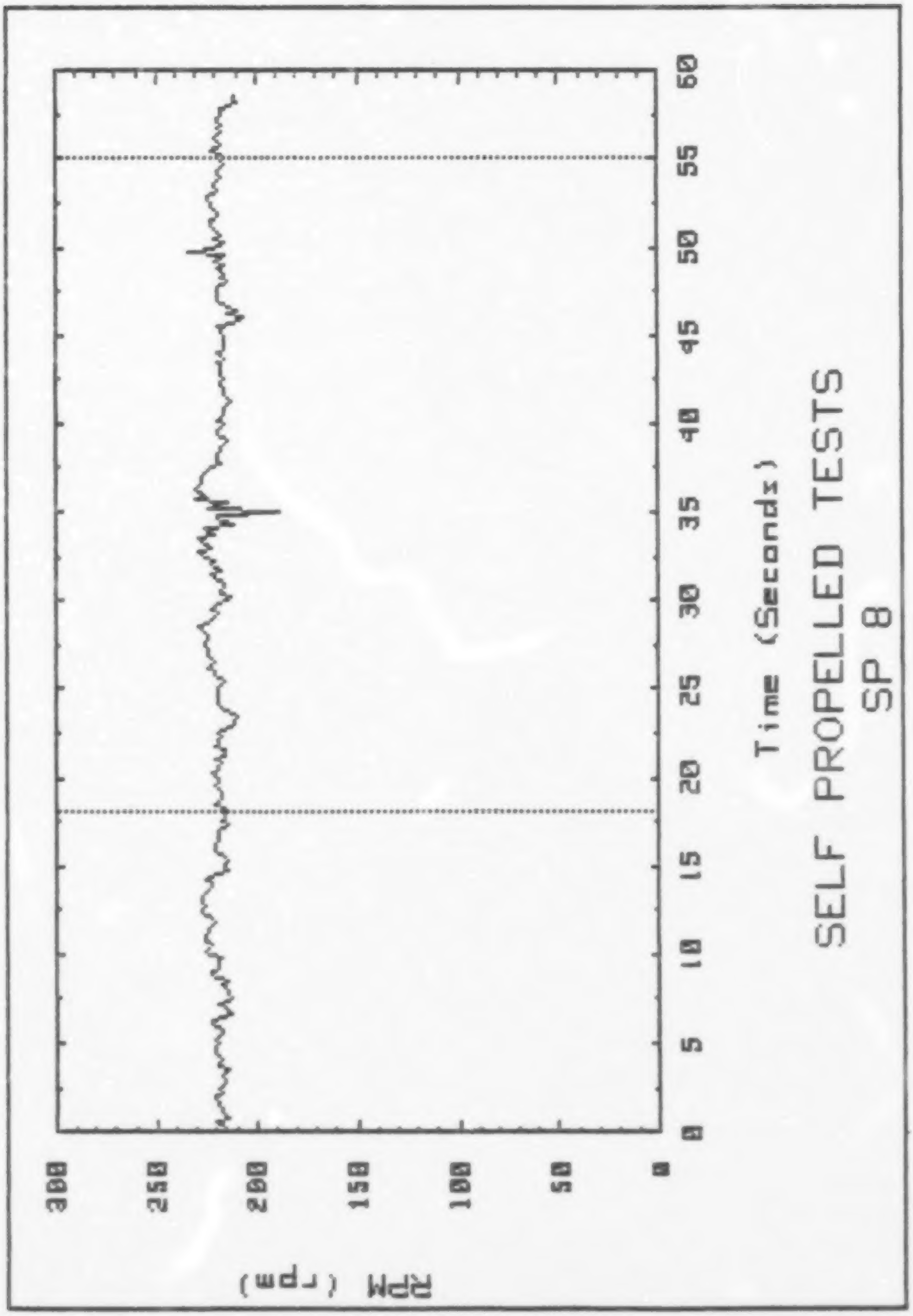
```
              Test Results for Test SP_8:  02/23/86, 15:45:09
              For the Interval Between  18  sec and  55  sec

             Average Ship Speed                   5.2   kts
             Average Thrust                   38350.0   lbs
             Average Torque                   40206.5   ft-lbs
             Average RPM                        218.9   RPM
             Average Shaft Horsepower          1675.6   HP
             Average Ice Thickness             1.2500   ft
             Mean Advance Coeff., Js           0.2857
             Thrust Coefficient, Kt          2.844E-01
             Torque Coefficient, Kq          3.508E-02

--------------------------------------------------------------------------------

                        RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs       2.895E+04                      2.593E+04
Thrust Deduction           2.452E-01                      3.240E-01
Propulsive Coeff.          2.783E-01                      2.492E-01

--------------------------------------------------------------------------------

                          Thrust Identity                Torque Identity

Advance Coefficient          -0.0012                        -0.0313
Thrust Coefficient            2.844E-01                      2.938E-01
Torque Coefficient            3.404E-02                      3.508E-02
Advance Velocity,fps          -.04                           -.97
Effective Wake                1.004E+00                      1.109E+00
Open Prop Eff.               -1.575E-03                     -4.156E-02
Relative Rotative Eff         9.704E-01                      9.680E-01
Hull Efficiency (Res. Form 1) -1.821E+02                    -6.900E+00
Hull Efficiency (Res. Form 2) -1.631E+02                    -6.180E+00
```



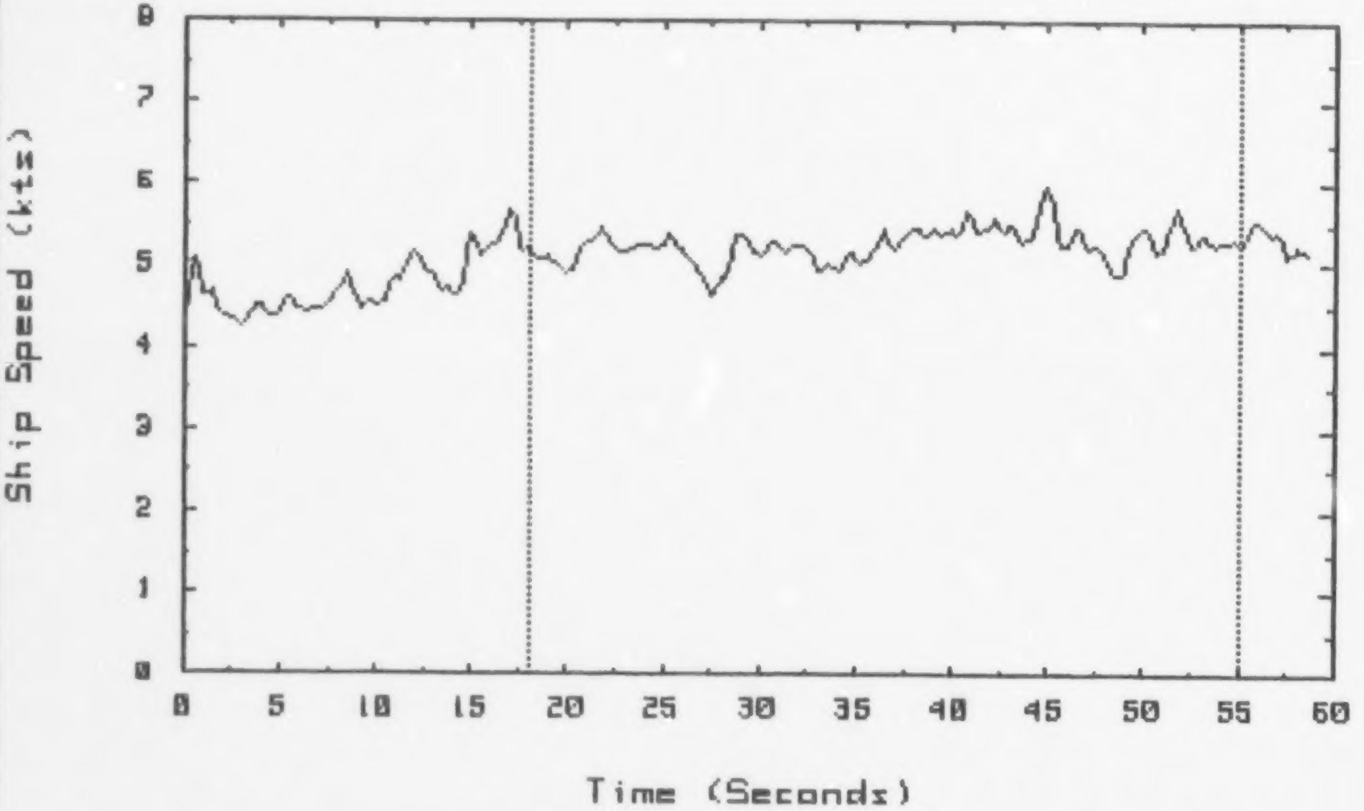
SELF PROPELLED TESTS
SP 8



SELF PROPELLED TESTS
SP 8

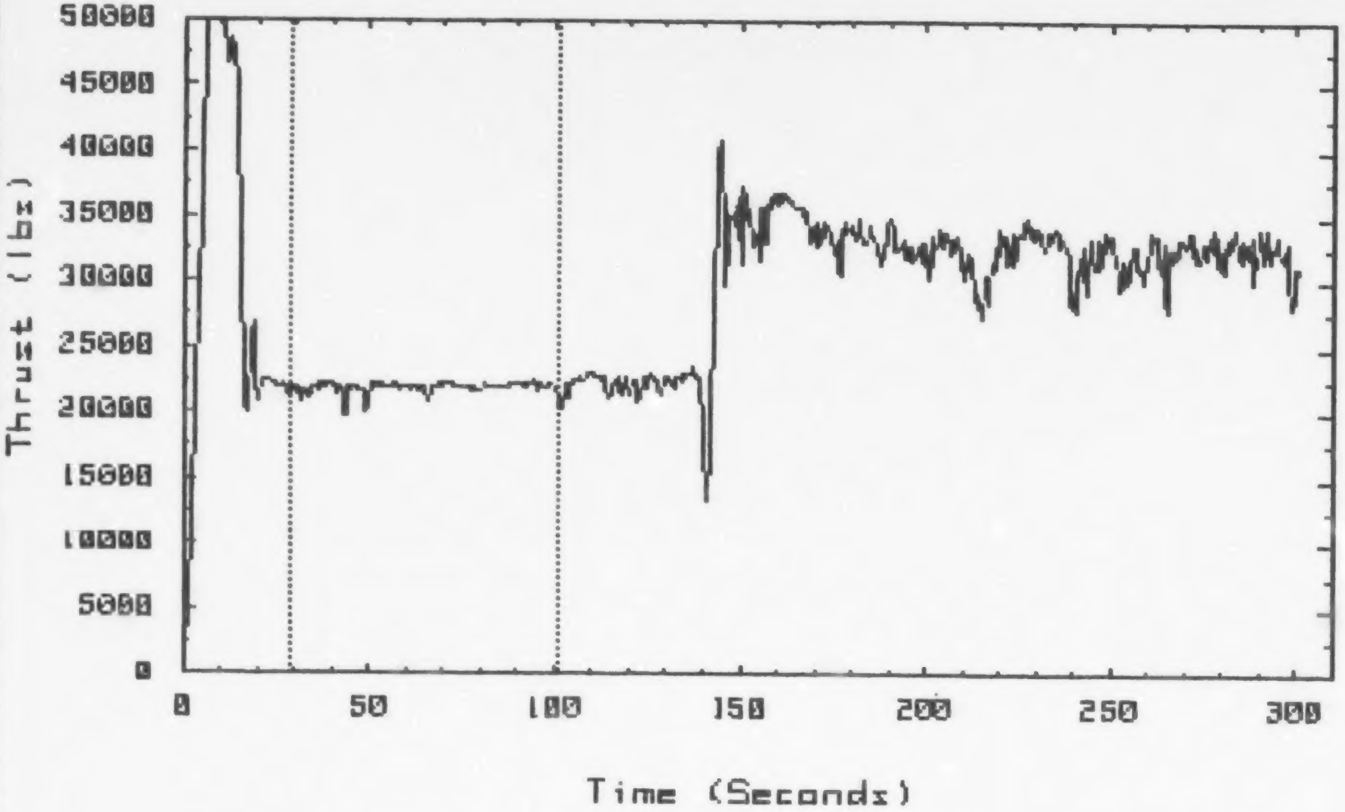


SELF PROPELLED TESTS
SP 8

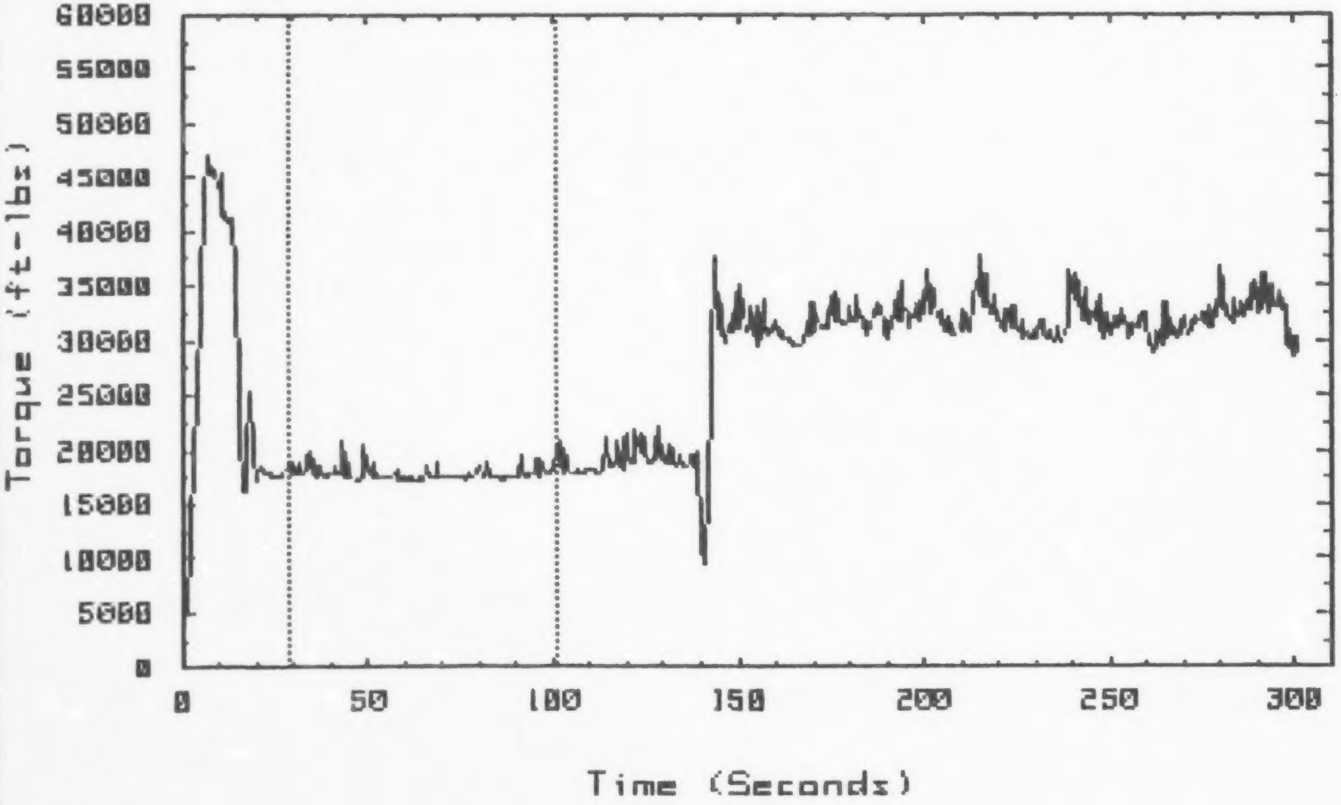


SELF PROPELLED TESTS
SP 8

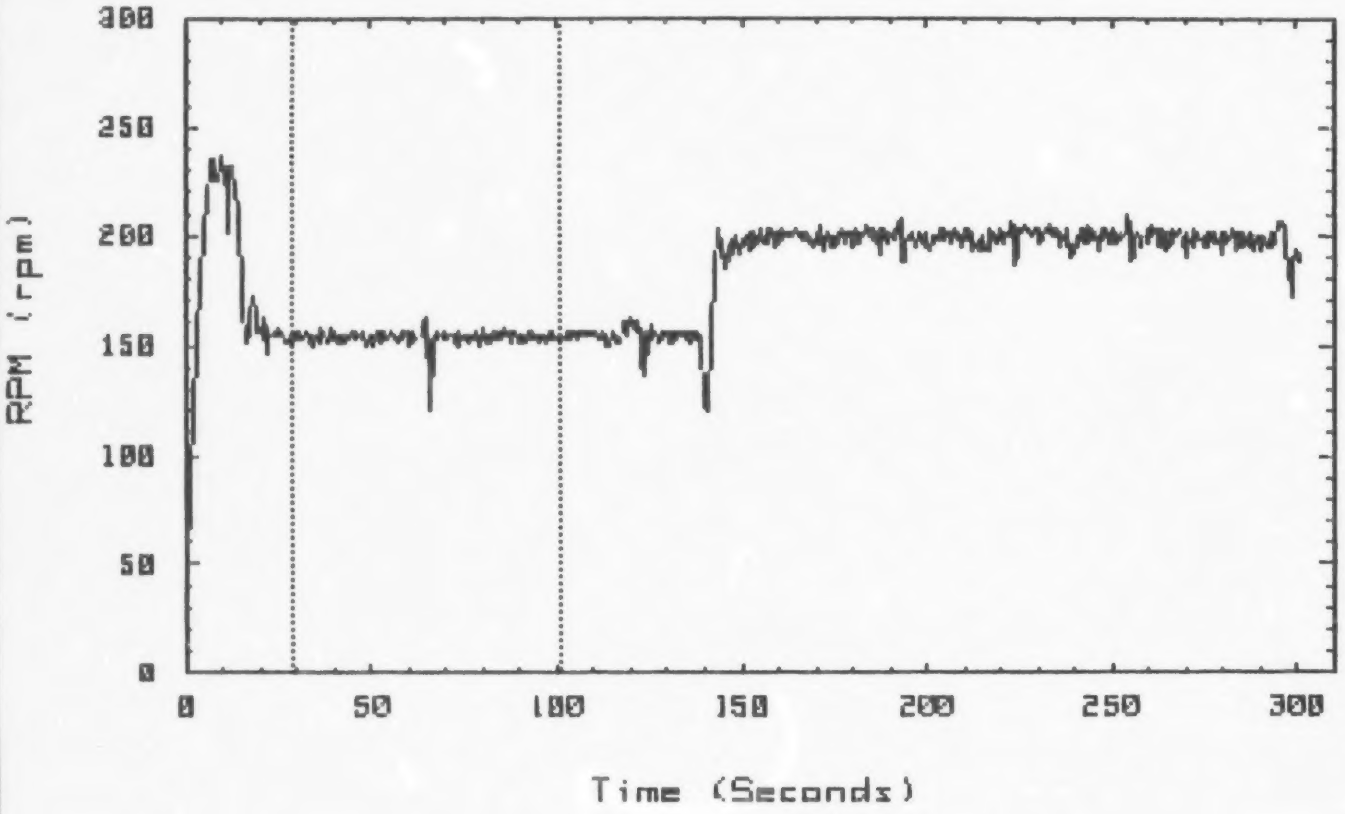
```
               Test Results for Test SP_9A:  02/23/86, 15:50:30
               For the Interval Between  29  sec and  101  sec

  CHANNEL                            MAXIMUM     MINIMUM       MEAN     STDRD DEV

  1  Thrust (lbs)                    22379.9     19731.2     21875.5        351.8
  2  Torque (ft-lbs)                 20887.2     17276.8     17933.5        594.3
  3  RPM (rpm)                         162.7       120.4       153.7          2.8
  4  Ship Speed (kts)                    2.7         2.0         2.4           .1
  6  Shaft Horsepower                  613.6       427.3       524.7         18.1


               Test Results for Test SP_9A:  02/23/86, 15:50:30
               For the Interval Between  29  sec and  101  sec

              Average Ship Speed                    2.4   kts
              Average Thrust                    21875.5   lbs
              Average Torque                    17933.5   ft-lbs
              Average RPM                         153.7   RPM
              Average Shaft Horsepower            524.7   HP
              Average Ice Thickness               .9167   ft
              Mean Advance Coeff., Js            0.1856
              Thrust Coefficient, Kt             3.293E-01
              Torque Coefficient, Kq             3.176E-02

------------------------------------------------------------------------------

                           RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs           1.165E+04                       1.163E+04
Thrust Deduction               4.673E-01                       4.683E-01
Propulsive Coeff.              1.632E-01                       1.629E-01

------------------------------------------------------------------------------

                             Thrust Identity                 Torque Identity

Advance Coefficient            -0.1490                         0.0642
Thrust Coefficient              3.293E-01                      2.635E-01
Torque Coefficient              3.988E-02                      3.176E-02
Advance Velocity,fps           -3.24                           1.40
Effective Wake                  1.802E+00                      6.542E-01
Open Prop Eff.                 -1.959E-01                      8.498E-02
Relative Rotative Eff           1.256E+00                      1.250E+00
Hull Efficiency (Res. Form 1)  -6.638E-01                      1.540E+00
Hull Efficiency (Res. Form 2)  -6.625E-01                      1.537E+00
```



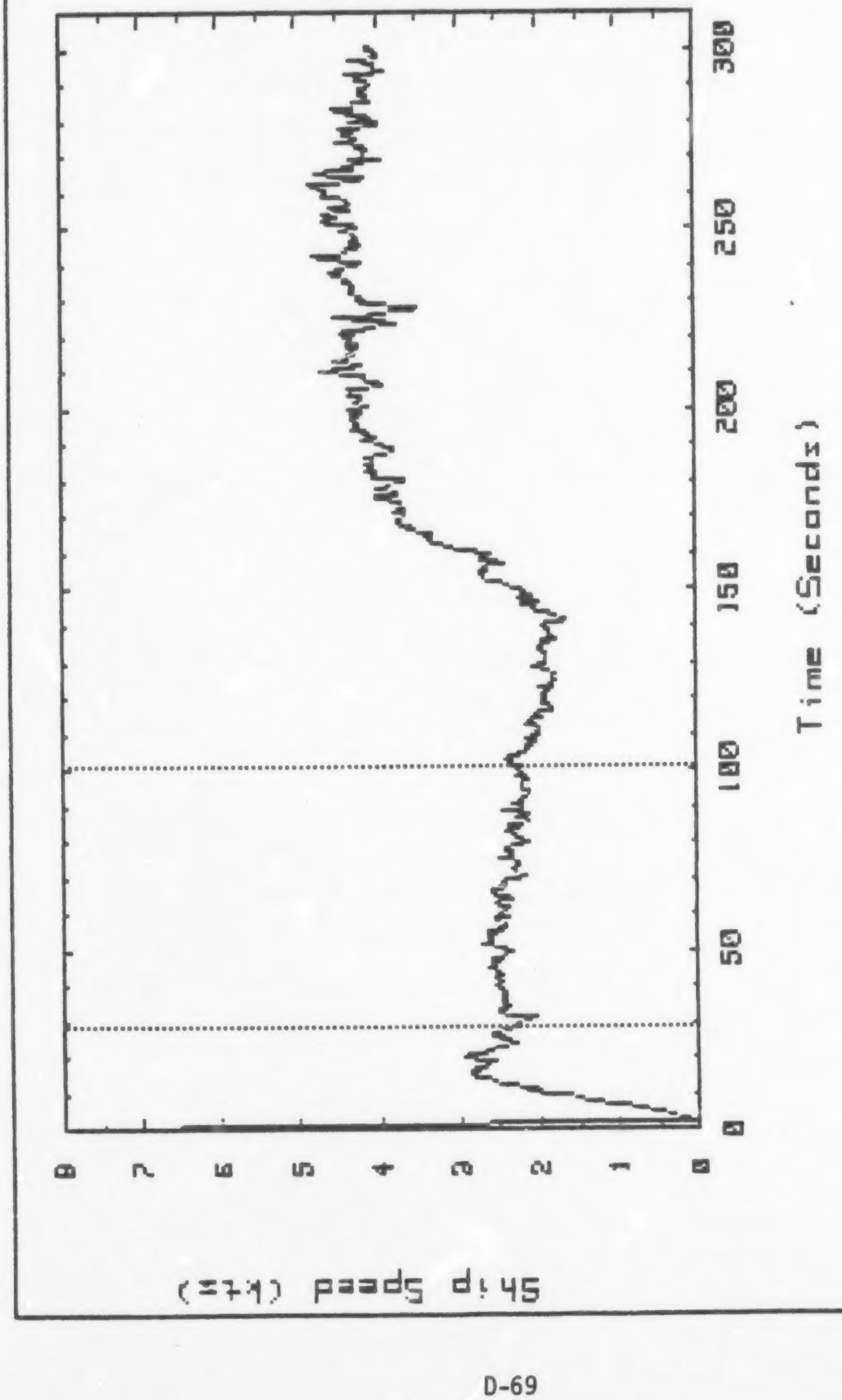
SELF PROPELLED TESTS
SP 9



SELF PROPELLED TESTS
SP 9

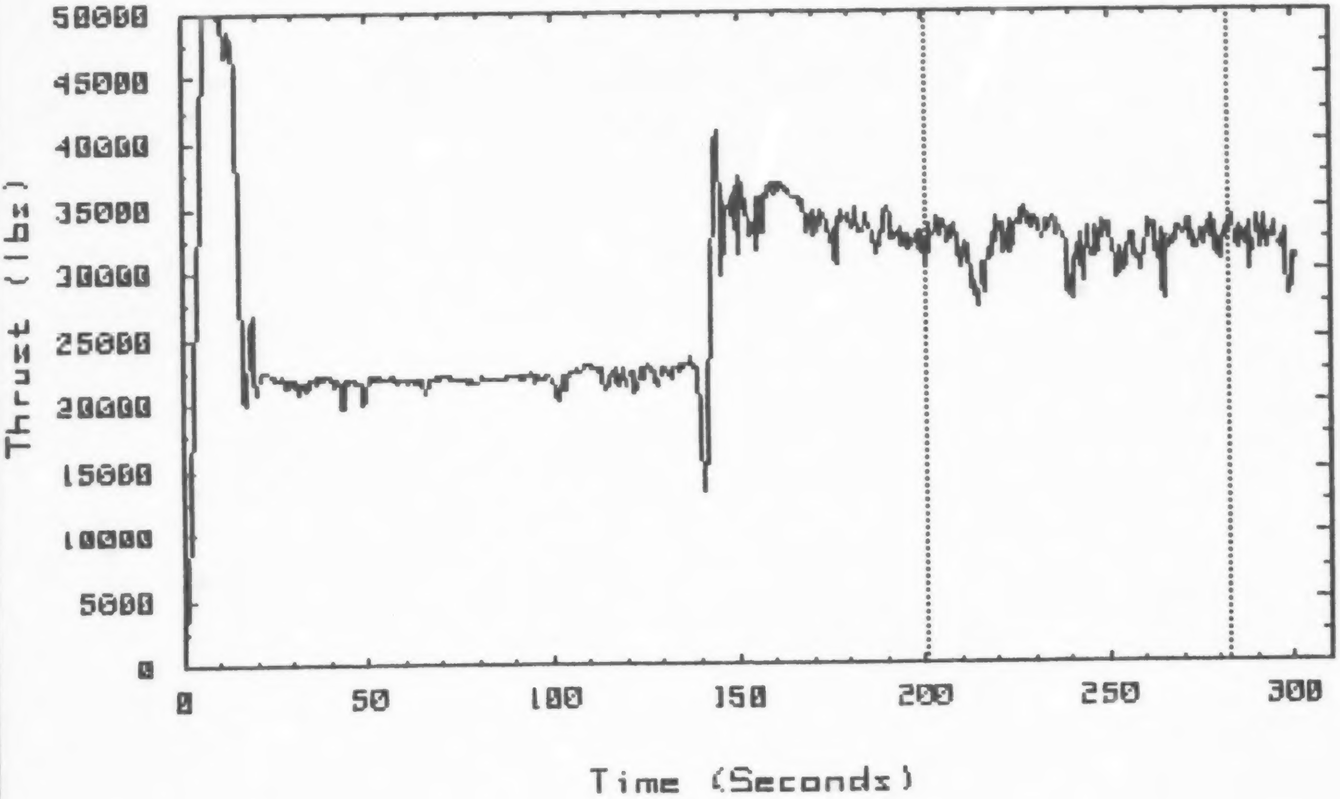


SELF PROPELLED TESTS
SP 9

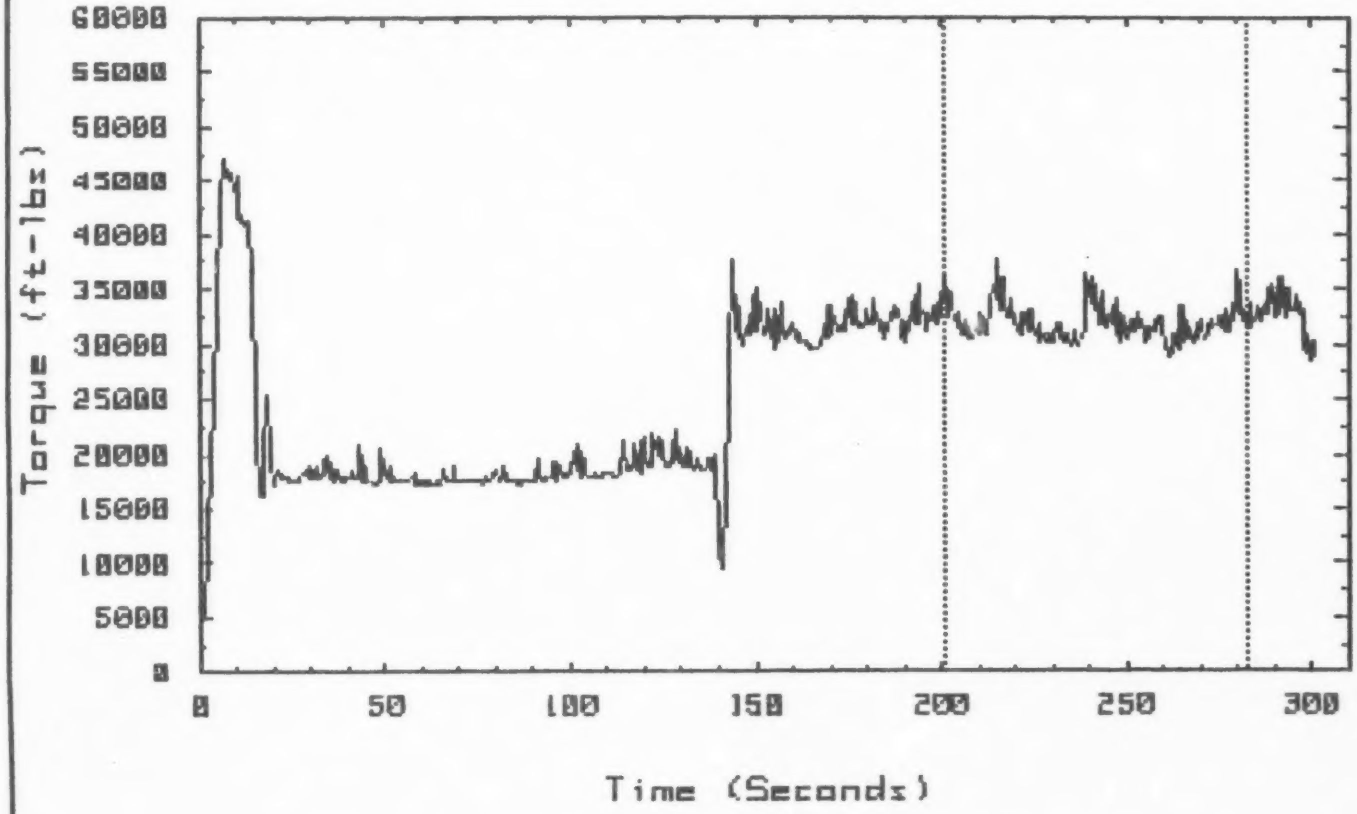


SELF PROPELLED TESTS
SP 9

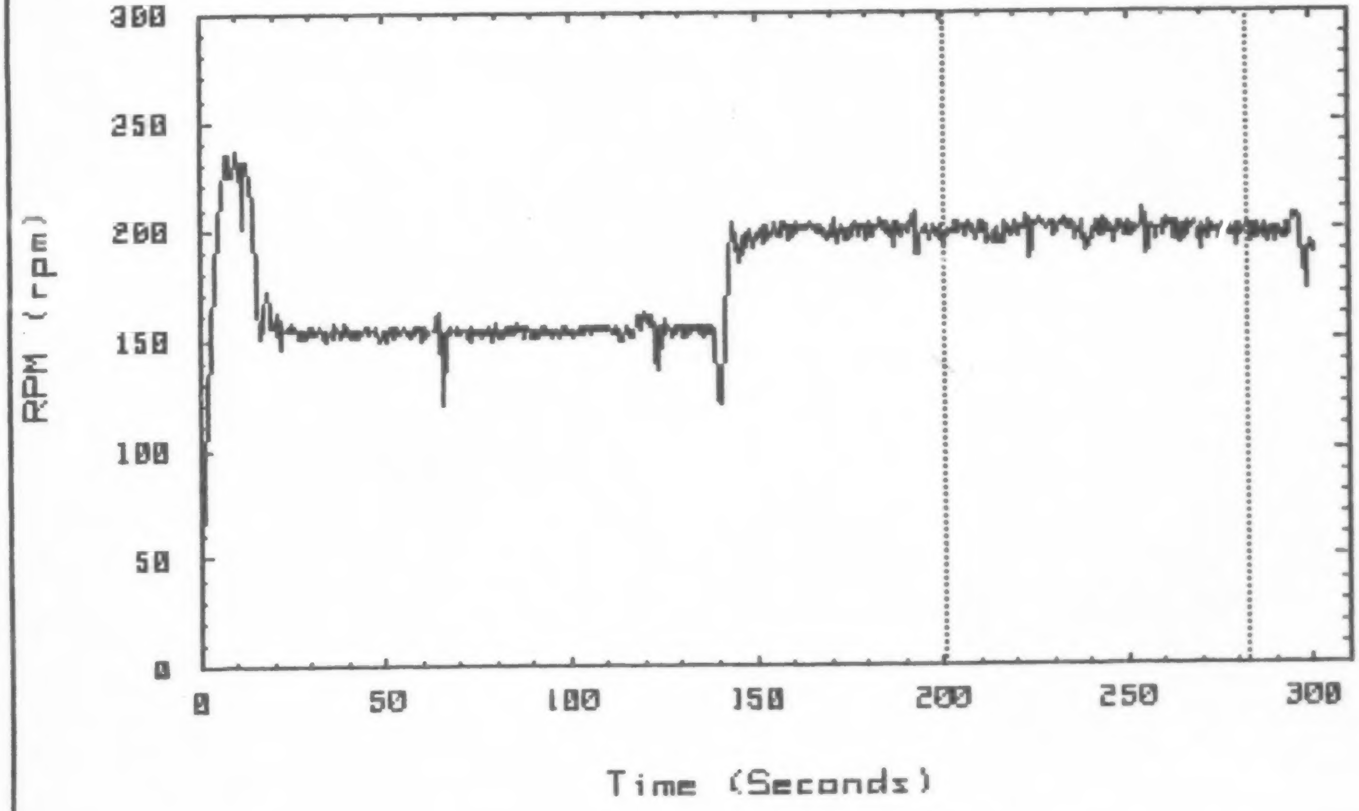
```
                Test Results for Test SP_9B:  02/23/86, 15:50:30
                For the Interval Between  201  sec and  283  sec

   CHANNEL                         MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                   34819.1     27204.2    32153.2      1485.0
 2  Torque (ft-lbs)                37681.9     29043.8    32020.3      1520.9
 3  RPM (rpm)                        208.5       186.0      199.5         3.2
 4  Ship Speed (kts)                   4.8         3.5        4.3          .2
 6  Shaft Horsepower                1416.0      1091.1     1215.7        54.0


                Test Results for Test SP_9B:  02/23/86, 15:50:30
                For the Interval Between  201  sec and  283  sec

               Average Ship Speed                 4.3    kts
               Average Thrust                 32153.2    lbs
               Average Torque                 32020.3    ft-lbs
               Average RPM                      199.5    RPM
               Average Shaft Horsepower        1215.7    HP
               Average Ice Thickness            .8750    ft
               Mean Advance Coeff., Js         0.2586
               Thrust Coefficient, Kt          2.873E-01
               Torque Coefficient, Kq          3.366E-02

------------------------------------------------------------------------------

                          RESISTANCE FORM 1             RESISTANCE FORM 2

Total Resistance,lbs          1.646E+04                     1.887E+04
Thrust Deduction              4.880E-01                     4.130E-01
Propulsive Coeff.             1.799E-01                     2.062E-01

------------------------------------------------------------------------------

                            Thrust Identity                Torque Identity

Advance Coefficient           -0.0104                       0.0093
Thrust Coefficient            2.873E-01                     2.811E-01
Torque Coefficient            3.438E-02                     3.366E-02
Advance Velocity,fps          -.29                           .26
Effective Wake                1.040E+00                     9.640E-01
Open Prop Eff.               -1.382E-02                     1.239E-02
Relative Rotative Eff         1.021E+00                     1.022E+00
Hull Efficiency (Res. Form 1) -1.275E+01                    1.420E+01
Hull Efficiency (Res. Form 2) -1.461E+01                    1.628E+01
```



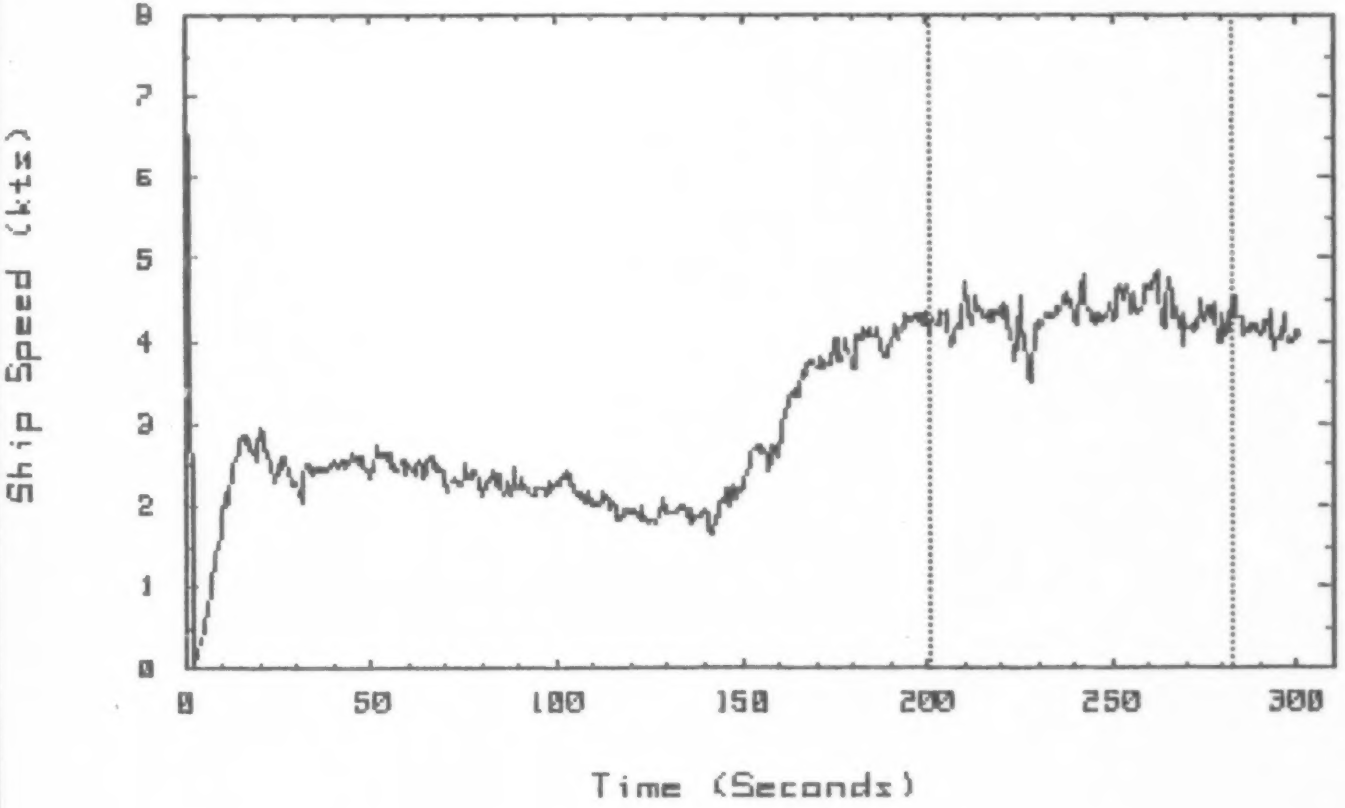
SELF PROPELLED TESTS
SP 9



SELF PROPELLED TESTS
SP 9

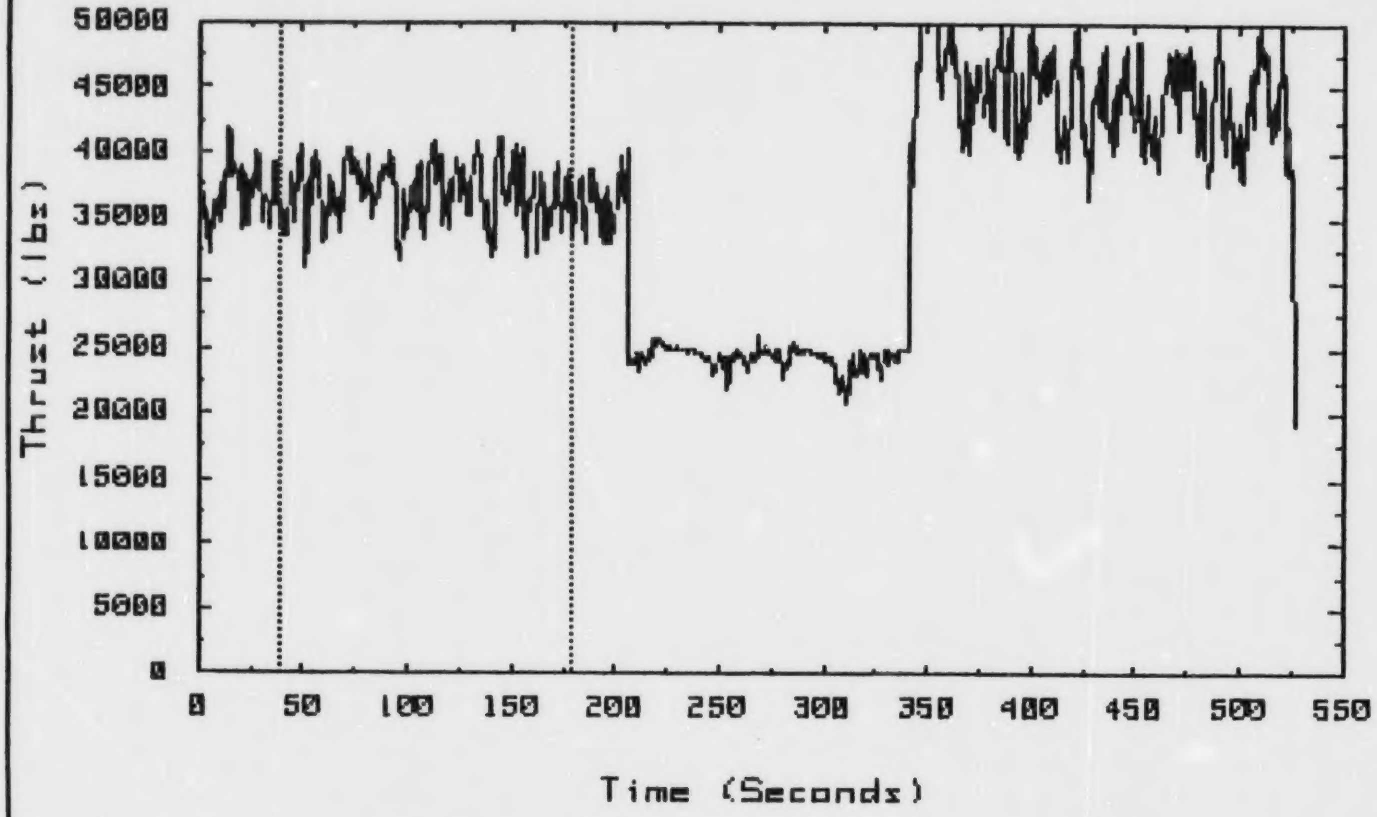


SELF PROPELLED TESTS
SP 9

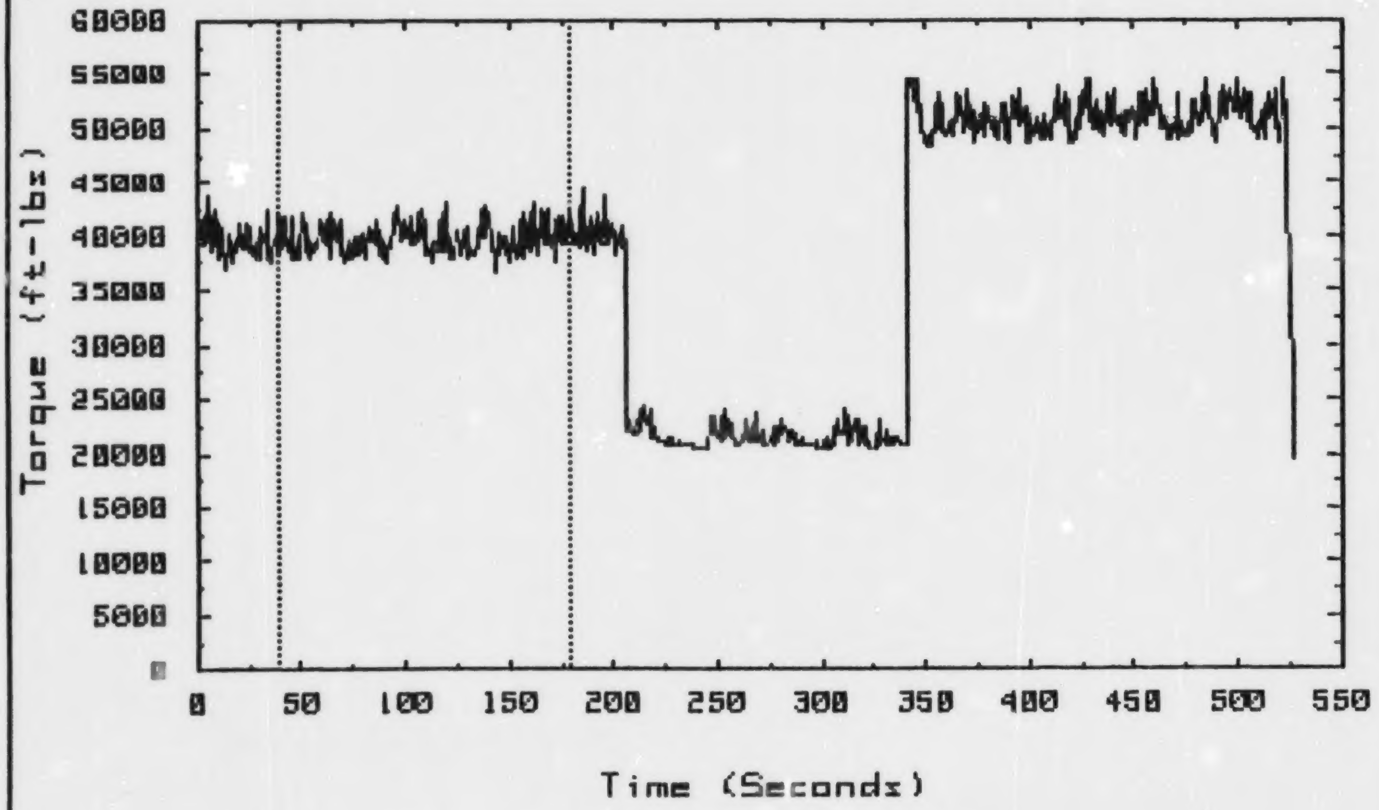


SELF PROPELLED TESTS
SP 9

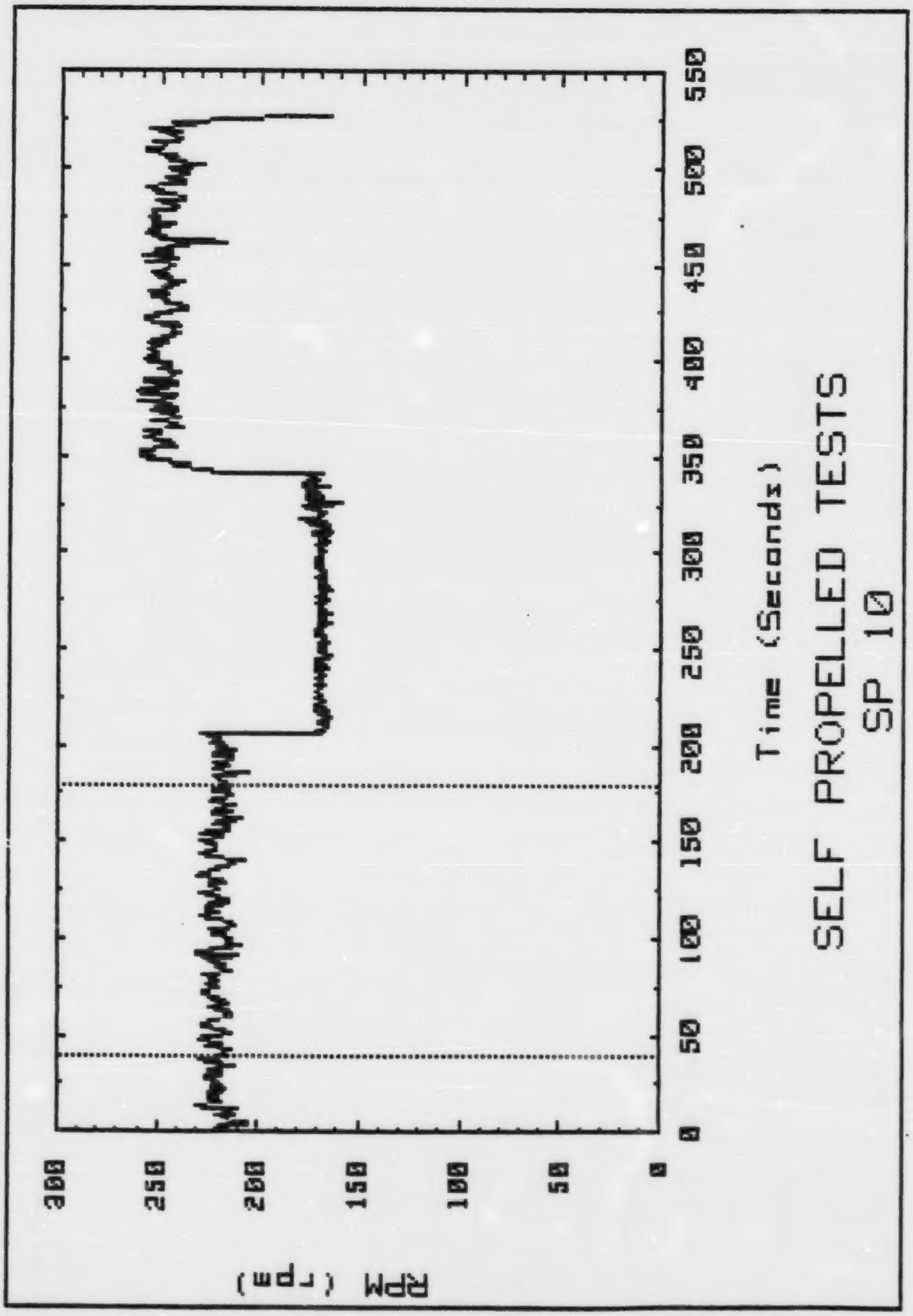
```
            Test Results for Test SP_10A:  02/23/86, 16:05:29
            For the Interval Between  39  sec and  180  sec

  CHANNEL                         MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                  41015.1     31224.5     36871.3     2027.1
 2  Torque (ft-lbs)               43297.9     36826.1     39882.1     1134.5
 3  RPM (rpm)                       230.5       205.5       220.1        4.3
 4  Ship Speed (kts)                  6.6         4.6         5.5         .3
 6  Shaft Horsepower               1776.6      1530.0      1670.5       33.1


            Test Results for Test SP_10A:  02/23/86, 16:05:29
            For the Interval Between  39  sec and  180  sec

           Average Ship Speed                   5.5    kts
           Average Thrust                   36871.3    lbs
           Average Torque                   39882.1    ft-lbs
           Average RPM                        220.1    RPM
           Average Shaft Horsepower          1670.5    HP
           Average Ice Thickness             1.0417    ft
           Mean Advance Coeff., Js           0.2956
           Thrust Coefficient, Kt          2.706E-01
           Torque Coefficient, Kq          3.444E-02

------------------------------------------------------------------------------

                           RESISTANCE FORM 1             RESISTANCE FORM 2

Total Resistance,lbs           2.408E+04                     2.527E+04
Thrust Deduction               3.470E-01                     3.147E-01
Propulsive Coeff.              2.414E-01                     2.533E-01

------------------------------------------------------------------------------

                            Thrust Identity               Torque Identity

Advance Coefficient            0.0422                       -0.0129
Thrust Coefficient             2.706E-01                     2.881E-01
Torque Coefficient             3.247E-02                     3.444E-02
Advance Velocity,fps           1.32                          -.40
Effective Wake                 8.571E-01                     1.044E+00
Open Prop Eff.                 5.601E-02                    -1.717E-02
Relative Rotative Eff          9.428E-01                     9.393E-01
Hull Efficiency (Res. Form 1)  4.571E+00                    -1.495E+01
Hull Efficiency (Res. Form 2)  4.797E+00                    -1.569E+01
```



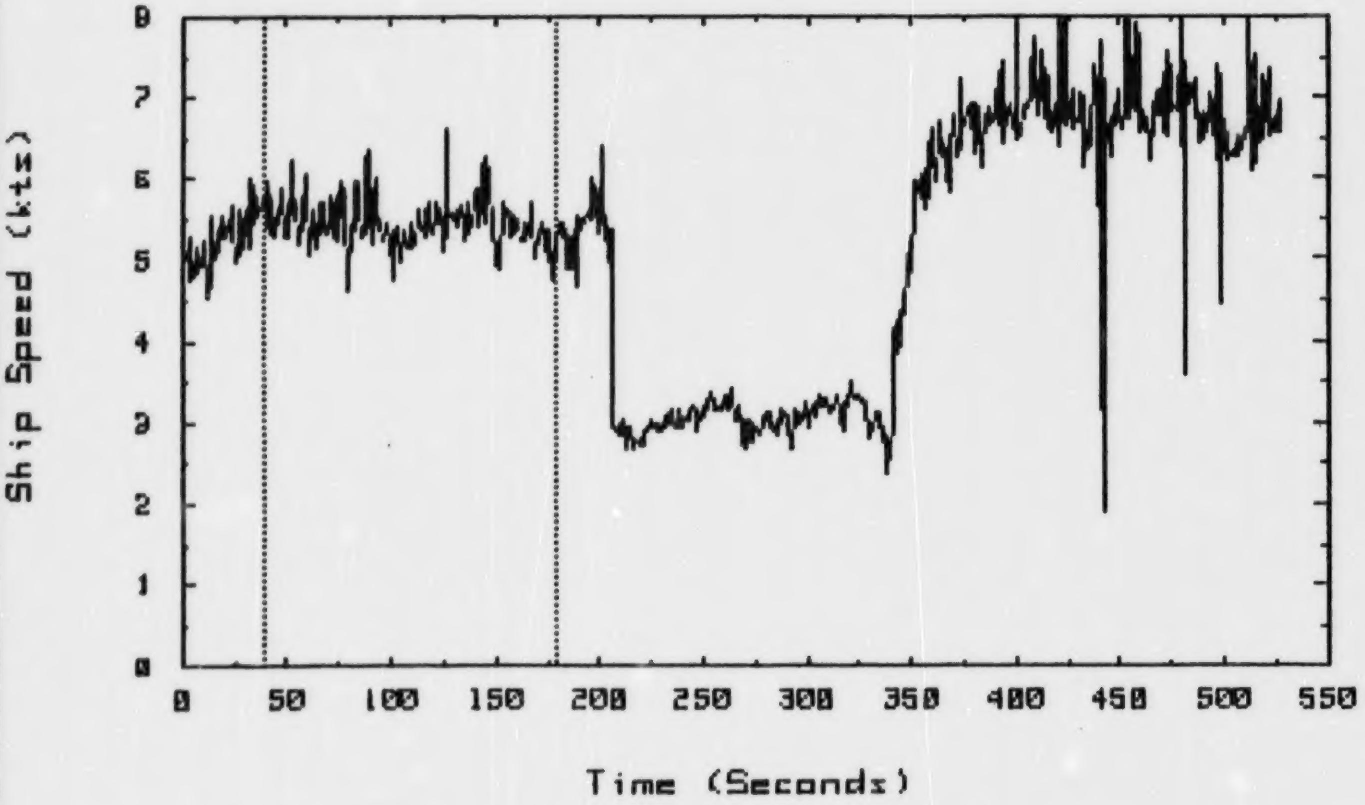
SELF PROPELLED TESTS
SP 10



SELF PROPELLED TESTS
SP 10



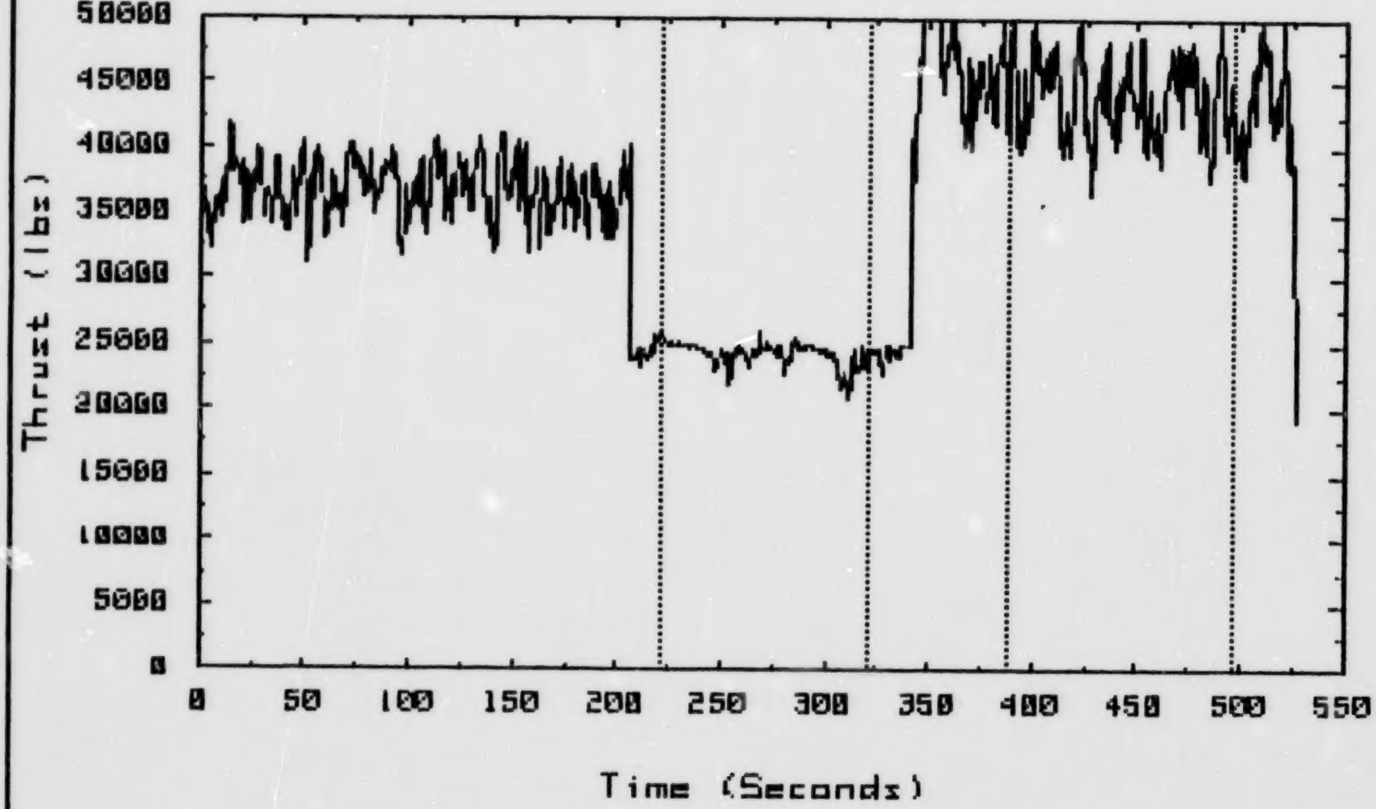
SELF PROPELLED TESTS
SP 10



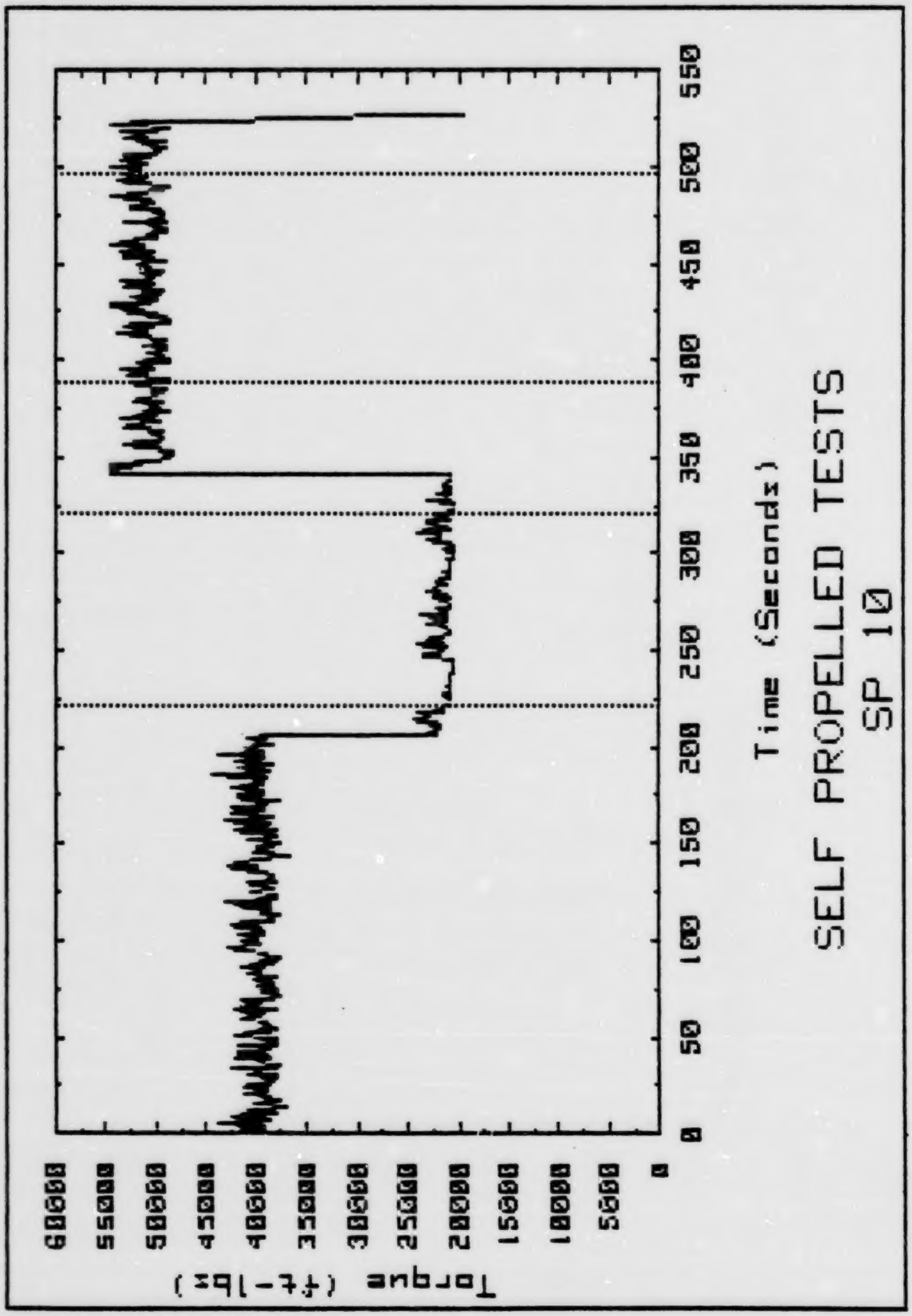
SELF PROPELLED TESTS
SP 10

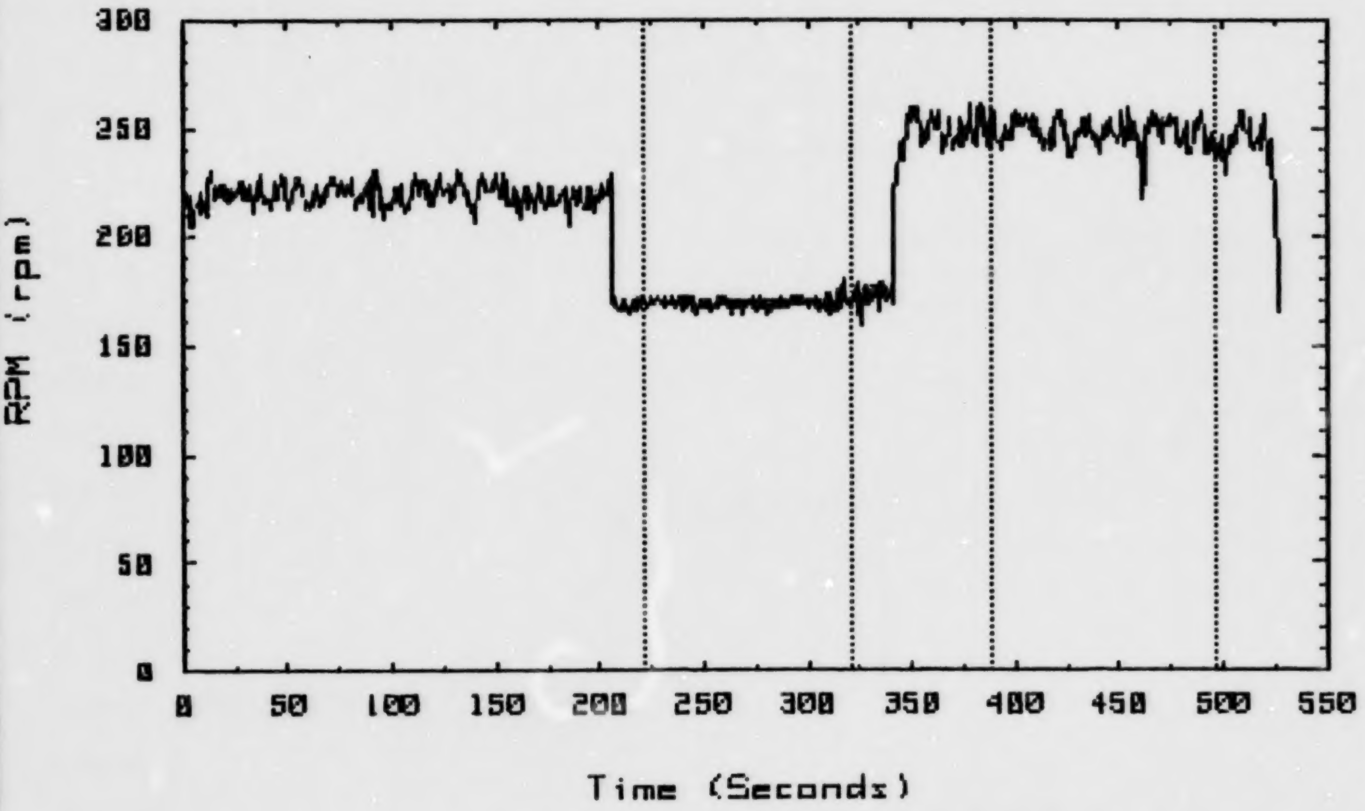
```
                Test Results for Test SP_108:  02/23/86, 16:05:29
                For the Interval Between  221  sec and  321  sec

     CHANNEL                         MAXIMUM     MINIMUM      MEAN     STDRD DEV

   1  Thrust (lbs)                   25879.9     20960.9     24323.0     765.9
   2  Torque (ft-lbs)                24042.9     20405.8     21431.9     771.0
   3  RPM (rpm)                        179.5       164.0       169.6       1.9
   4  Ship Speed (kts)                   3.5         2.7         3.1        .1
   6  Shaft Horsepower                 782.4       648.2       691.9      24.2


                Test Results for Test SP_108:  02/23/86, 16:05:29
                For the Interval Between  221  sec and  321  sec

               Average Ship Speed                 3.1    kts
               Average Thrust                 24323.0    lbs
               Average Torque                 21431.9    ft-lbs
               Average RPM                      169.6    RPM
               Average Shaft Horsepower         691.9    HP
               Average Ice Thickness           1.2917    ft
               Mean Advance Coeff., Js         0.2172
               Thrust Coefficient, Kt          3.007E-01
               Torque Coefficient, Kq          3.117E-02

------------------------------------------------------------------------------

                         RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs         2.118E+04                      1.973E+04
Thrust Deduction             1.294E-01                      1.888E-01
Propulsive Coeff.            2.903E-01                      2.705E-01

------------------------------------------------------------------------------

                           Thrust Identity                Torque Identity

Advance Coefficient            -0.0535                      0.0812
Thrust Coefficient              3.007E-01                   2.579E-01
Torque Coefficient              3.601E-02                   3.117E-02
Advance Velocity,fps           -1.28                        1.95
Effective Wake                  1.246E+00                   6.260E-01
Open Prop Eff.                 -7.106E-02                   1.073E-01
Relative Rotative Eff           1.156E+00                   1.166E+00
Hull Efficiency (Res. Form 1)  -3.535E+00                   2.328E+00
Hull Efficiency (Res. Form 2)  -3.294E+00                   2.169E+00
```

```
          Test Results for Test SP_10C:  02/23/86, 16:05:29
          For the Interval Between  388  sec and  496  sec

  CHANNEL                        MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                 50427.4     36616.5     44151.6      2884.2
 2  Torque (ft-lbs)              54503.3     48646.6     51045.5      1231.5
 3  RPM (rpm)                      259.0       217.7       248.5         5.4
 4  Ship Speed (kts)                 9.8         1.9         6.9          .5
 6  Shaft Horsepower              2546.3      2144.5      2414.3        41.6


          Test Results for Test SP_10C:  02/23/86, 16:05:29
          For the Interval Between  388  sec and  496  sec

         Average Ship Speed                 6.9    kts
         Average Thrust                 44151.6    lbs
         Average Torque                 51045.5    ft-lbs
         Average RPM                      248.5    RPM
         Average Shaft Horsepower        2414.3    HP
         Average Ice Thickness           1.2917    ft
         Mean Advance Coeff., Js         0.3296
         Thrust Coefficient, Kt          2.542E-01
         Torque Coefficient, Kq          3.457E-02

-------------------------------------------------------------------------

                       RESISTANCE FORM 1            RESISTANCE FORM 2

Total Resistance,lbs        3.728E+04                    3.447E+04
Thrust Deduction            1.557E-01                    2.192E-01
Propulsive Coeff.           3.256E-01                    3.011E-01

-------------------------------------------------------------------------

                           Thrust Identity             Torque Identity

Advance Coefficient         0.0928                      -0.0166
Thrust Coefficient          2.542E-01                    2.893E-01
Torque Coefficient          3.068E-02                    3.457E-02
Advance Velocity,fps        3.27                        -.59
Effective Wake              7.184E-01                    1.050E+00
Open Prop Eff.              1.223E-01                   -2.213E-02
Relative Rotative Eff       8.876E-01                    8.786E-01
Hull Efficiency (Res. Form 1)  2.998E+00                -1.672E+01
Hull Efficiency (Res. Form 2)  2.772E+00                -1.546E+01
```

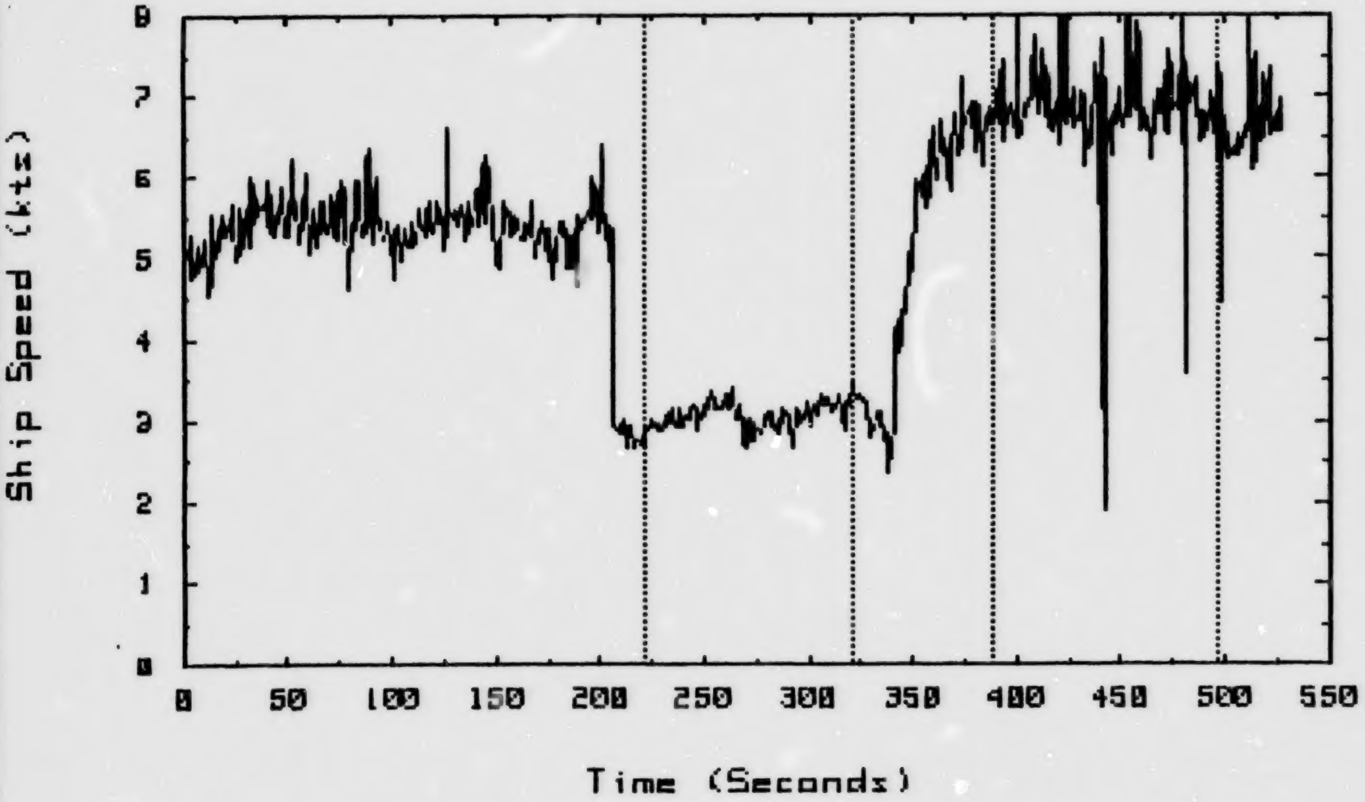


SELF PROPELLED TESTS
SP 10


SELF PROPELLED TESTS
SP 10

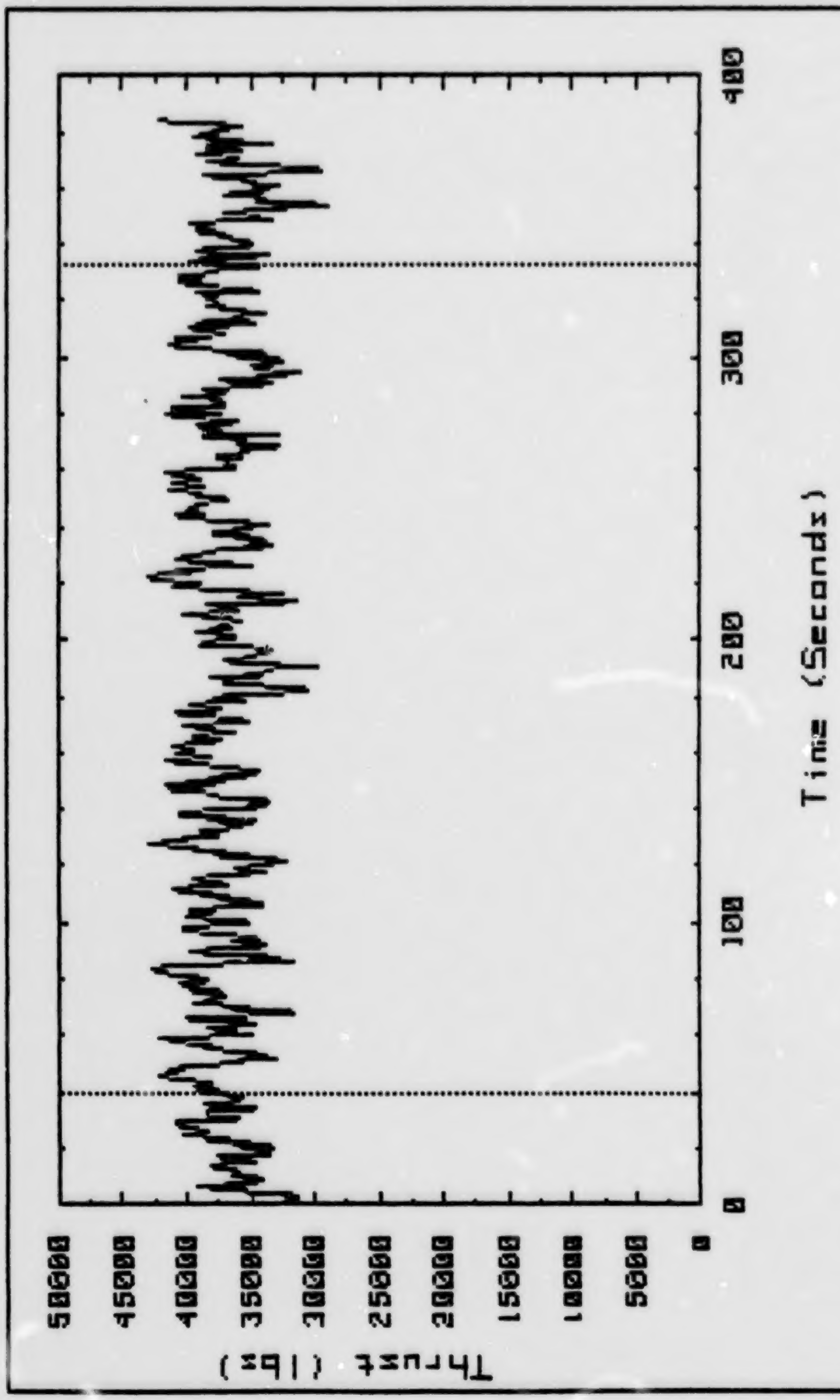


SELF PROPELLED TESTS
SP 10

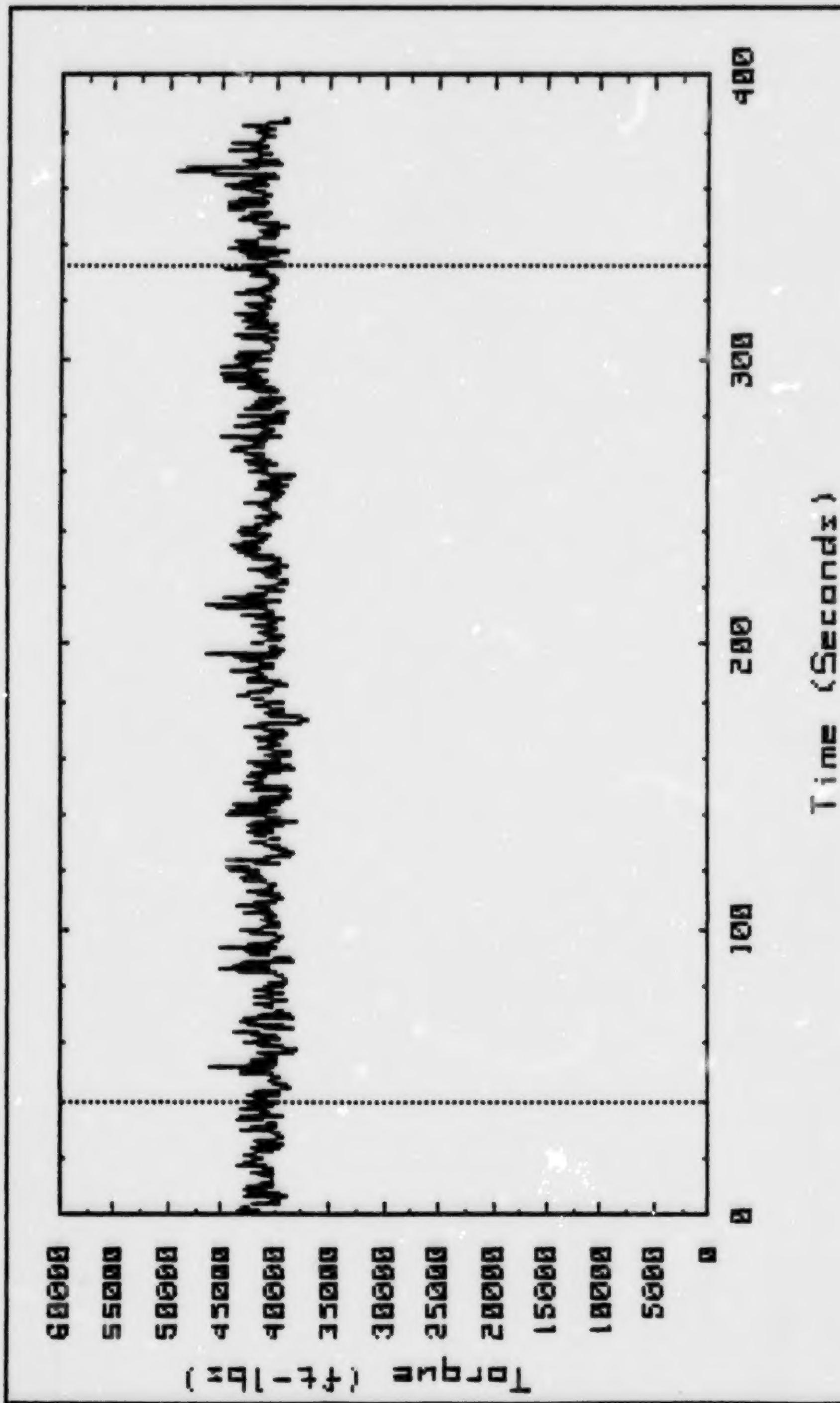


SELF PROPELLED TESTS
SP 10

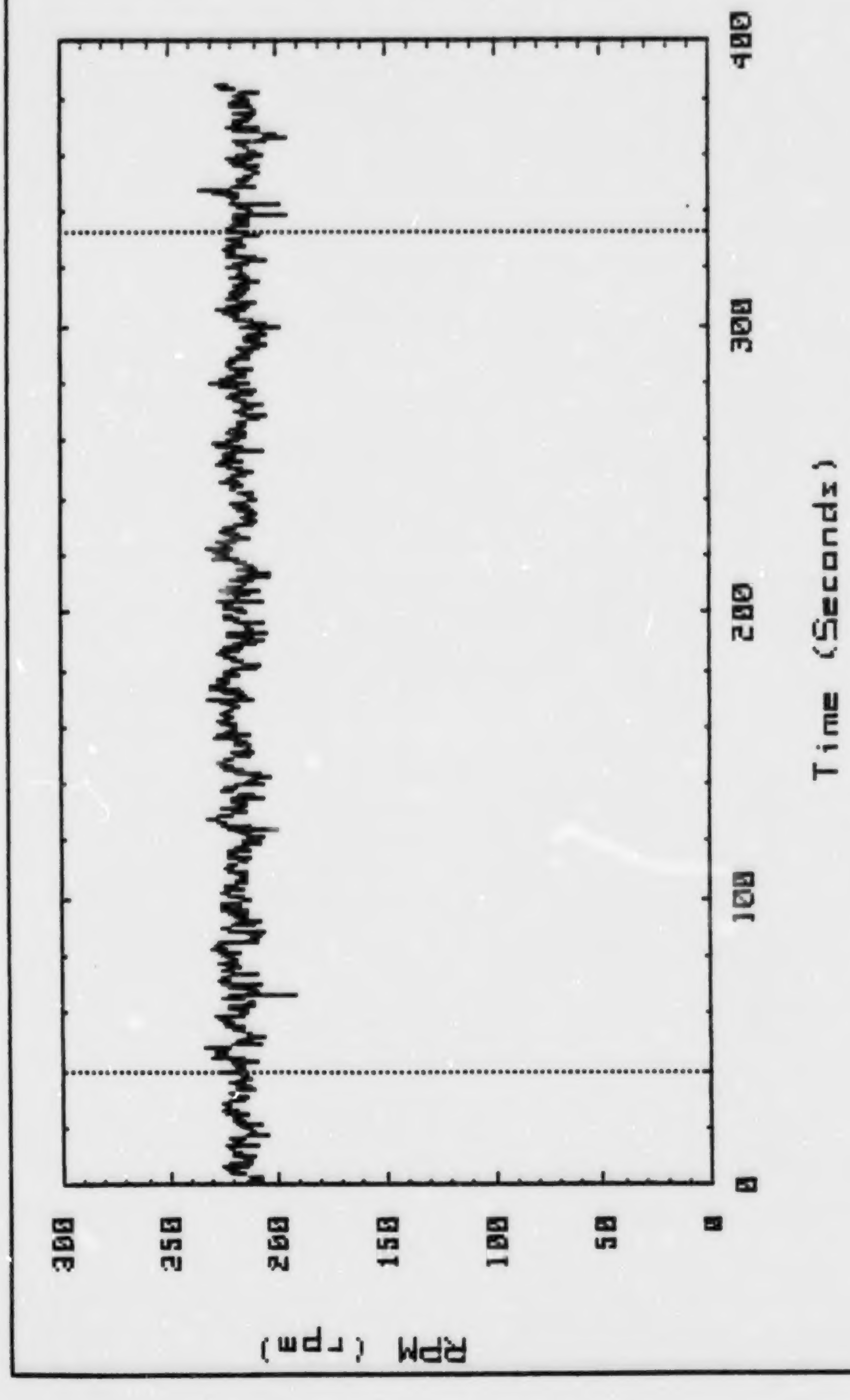
```
              Test Results for Test SP_11:  02/24/86, 08:13:27
              For the Interval Between  40  sec and  333  sec

   CHANNEL                          MAXIMUM      MINIMUM      MEAN       STDRD DEV

 1  Thrust (lbs)                    43074.6      29642.1    37521.3       2428.4
 2  Torque (ft-lbs)                 46522.6      37002.0    41104.9       1359.1
 3  RPM (rpm)                         233.4        191.4      218.3          5.3
 4  Ship Speed (kts)                    6.8          4.5        5.4           .3
 6  Shaft Horsepower                 1888.0       1484.6     1707.9         42.4


              Test Results for Test SP_11:  02/24/86, 08:13:27
              For the Interval Between  40  sec and  333  sec

             Average Ship Speed                  5.4    kts
             Average Thrust                  37521.3    lbs
             Average Torque                  41104.9    ft-lbs
             Average RPM                       218.3    RPM
             Average Shaft Horsepower         1707.9    HP
             Average Ice Thickness            1.1667    ft
             Mean Advance Coeff., Js          0.2950
             Thrust Coefficient, Kt           2.798E-01
             Torque Coefficient, Kq           3.606E-02

--------------------------------------------------------------------------------

                        RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs        2.726E+04                       2.571E+04
Thrust Deduction            2.735E-01                       3.147E-01
Propulsive Coeff.           2.647E-01                       2.496E-01

--------------------------------------------------------------------------------

                          Thrust Identity                 Torque Identity

Advance Coefficient         0.0135                          -0.0590
Thrust Coefficient          2.798E-01                        3.024E-01
Torque Coefficient          3.351E-02                        3.606E-02
Advance Velocity,fps         .42                            -1.83
Effective Wake              9.543E-01                        1.200E+00
Open Prop Eff.              1.792E-02                       -7.840E-02
Relative Rotative Eff       9.291E-01                        9.253E-01
Hull Efficiency (Res. Form 1)  1.590E+01                    -3.631E+00
Hull Efficiency (Res. Form 2)  1.500E+01                    -3.425E+00
```



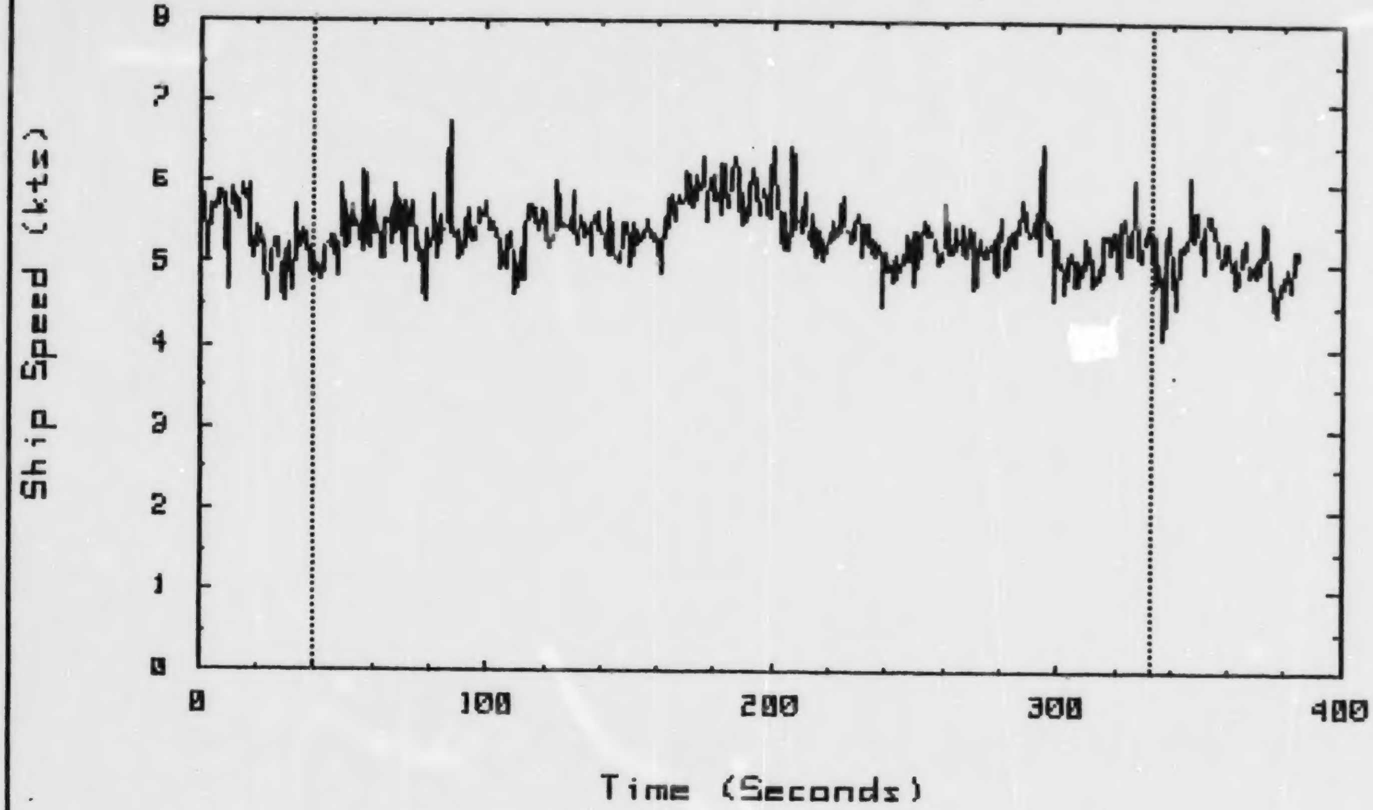
SELF PROPELLED TESTS
SP 11



SELF PROPELLED TESTS
SP 11

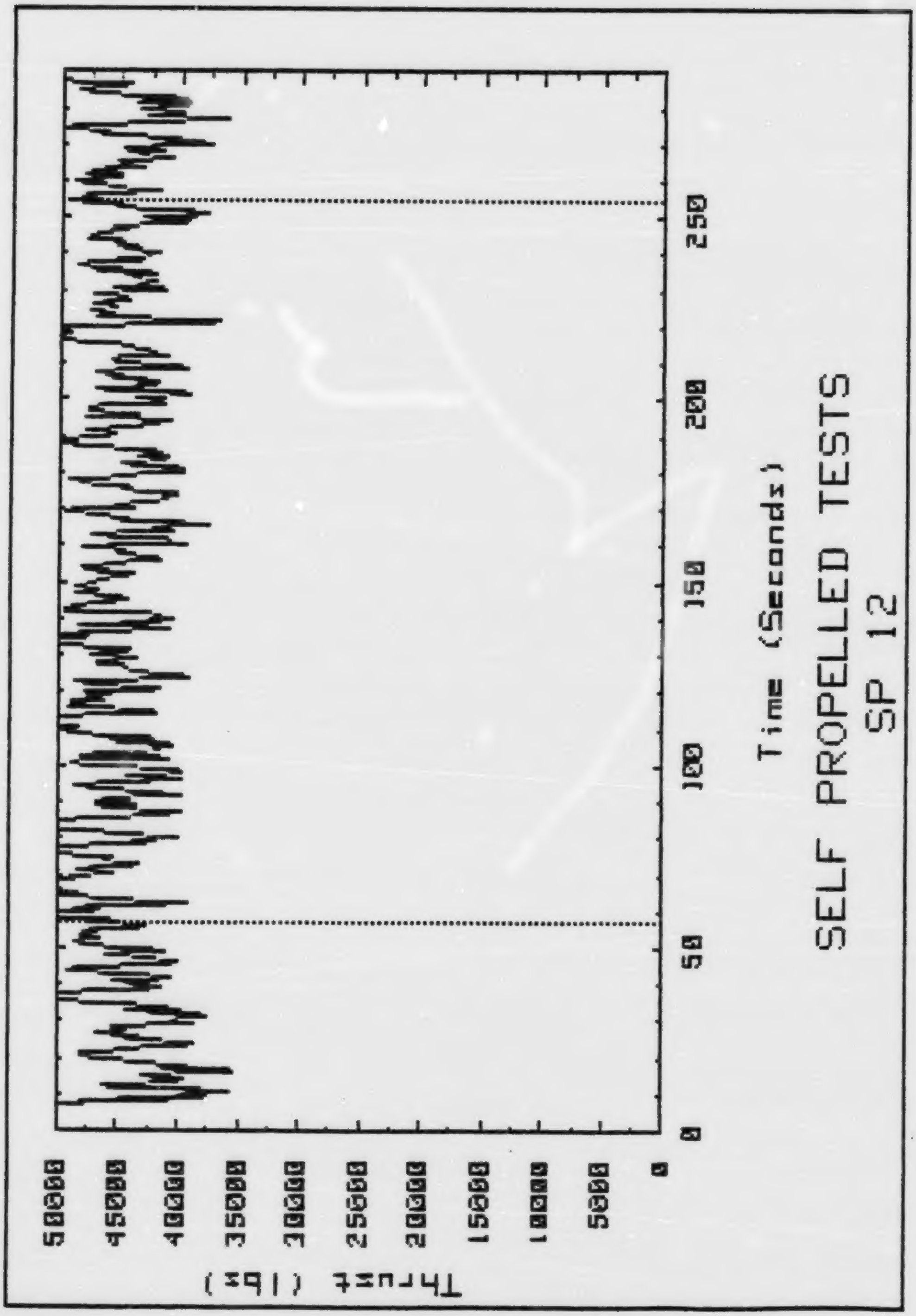


SELF PROPELLED TESTS
SP 11

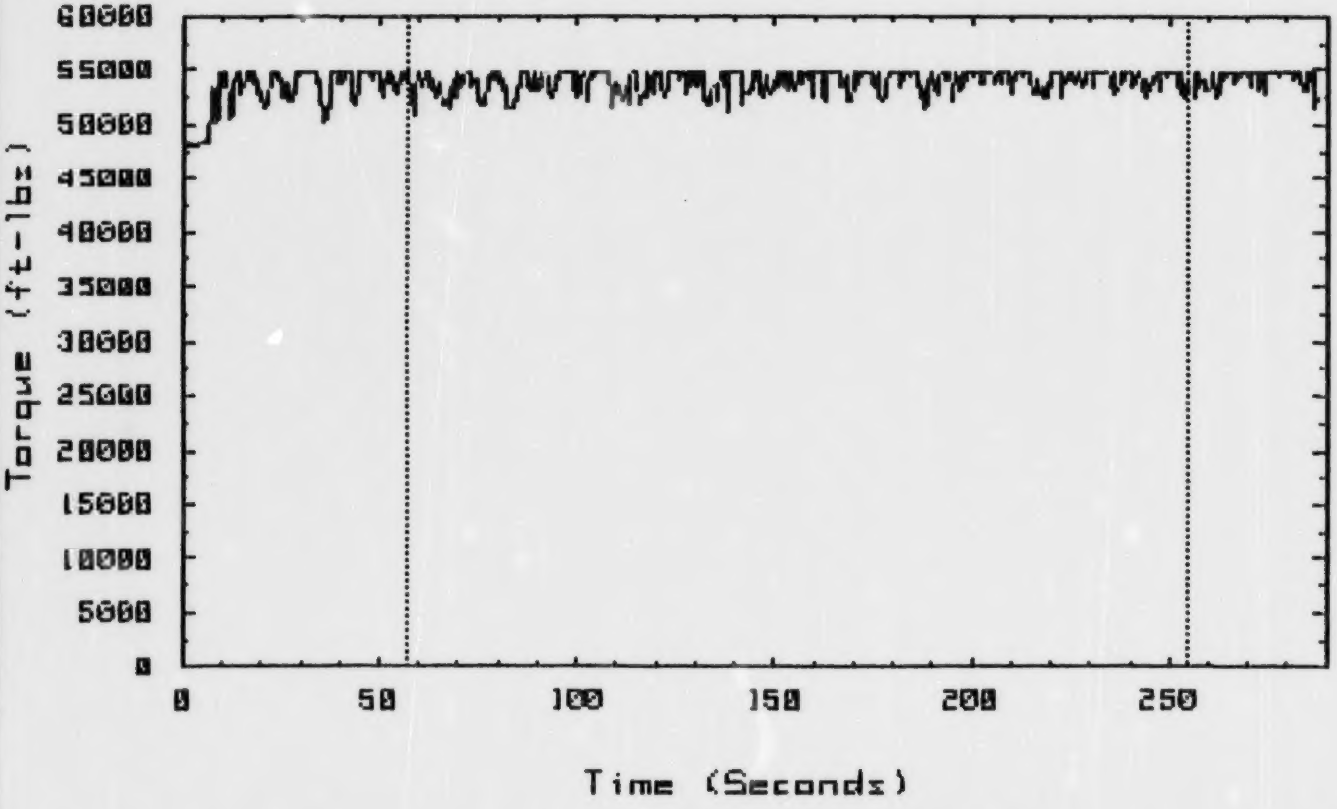


SELF PROPELLED TESTS
SP 11

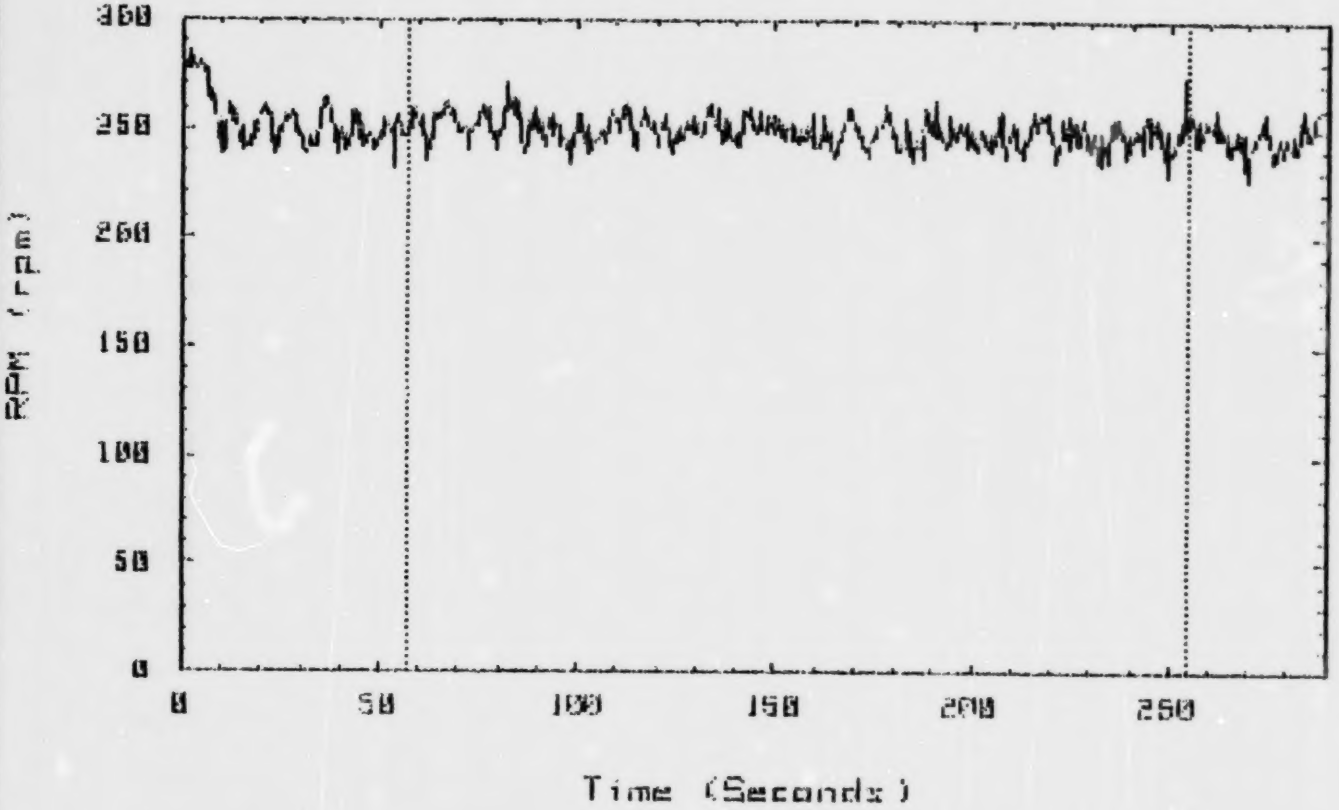
```
                 Test Results for Test SP_12:  02/24/86, 08:31:40
                 For the Interval Between  57  sec and  255  sec

    CHANNEL                          MAXIMUM     MINIMUM      MEAN     STDRD DEV

  1  Thrust (lbs)                    53196.3     36784.0    45307.7      3063.3
  2  Torque (ft-lbs)                 54893.2     50962.0    54076.8       920.1
  3  RPM (rpm)                         273.8       228.2      249.5         5.8
  4  Ship Speed (kts)                   10.3         5.7        6.8          .4
  6  Shaft Horsepower                 2751.7      2370.4     2568.1        43.8


                 Test Results for Test SP_12:  02/24/86, 08:31:40
                 For the Interval Between  57  sec and  255  sec

                Average Ship Speed                    6.8    kts
                Average Thrust                    45307.7    lbs
                Average Torque                    54076.8    ft-lbs
                Average RPM                         249.5    RPM
                Average Shaft Horsepower           2568.1    HP
                Average Ice Thickness              1.0417    ft
               'Mean Advance Coeff., Js           0.3236
                Thrust Coefficient, Kt            2.588E-01
                Torque Coefficient, Kq            3.633E-02

--------------------------------------------------------------------------------

                              RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs              2.889E+04                      3.373E+04
Thrust Deduction                  3.624E-01                      2.555E-01
Propulsive Coeff.                 2.338E-01                      2.731E-01

--------------------------------------------------------------------------------

                                Thrust Identity                Torque Identity

Advance Coefficient               0.0788                        -0.0667
Thrust Coefficient                2.588E-01                      3.047E-01
Torque Coefficient                3.117E-02                      3.633E-02
Advance Velocity,fps              2.79                          -2.36
Effective Wake                    7.564E-01                      1.206E+00
Open Prop Eff.                    1.041E-01                     -9.857E-02
Relative Rotative Eff             8.579E-01                      8.491E-01
Hull Efficiency (Res. Form 1)     2.618E+00                     -3.093E+00
Hull Efficiency (Res. Form 2)     3.057E+00                     -3.612E+00
```



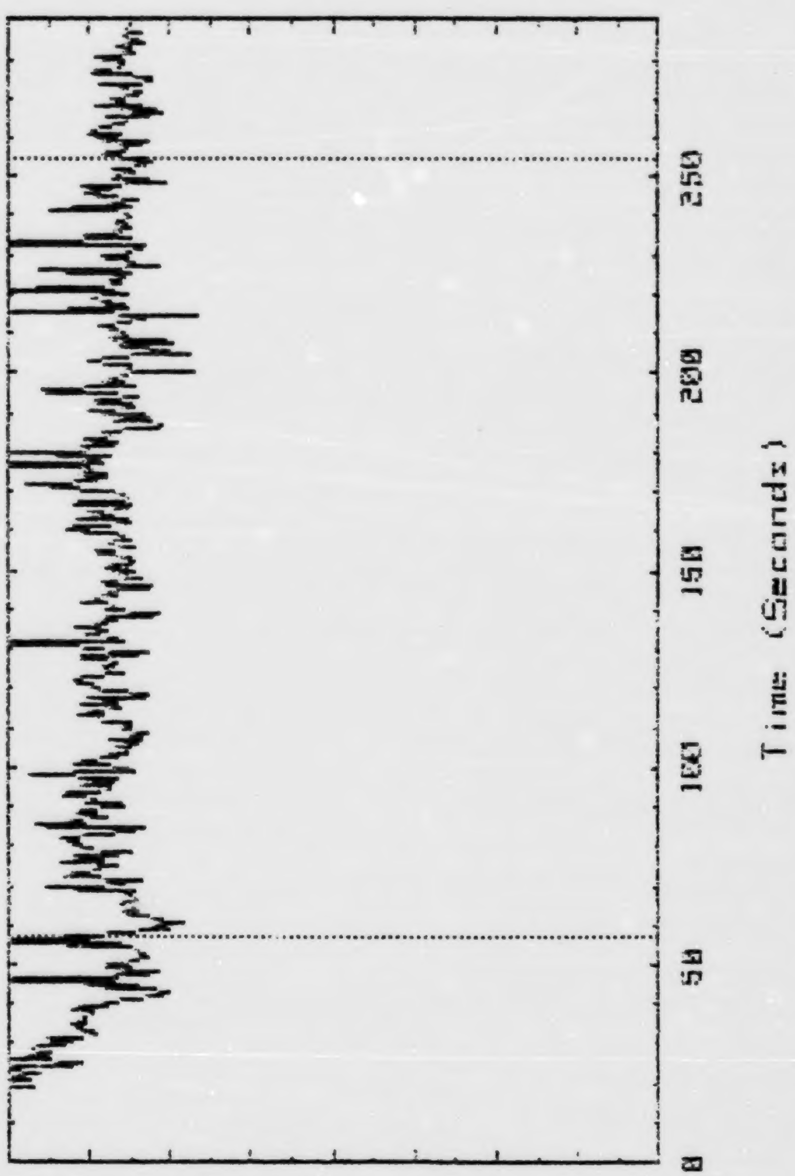
SELF PROPELLED TESTS
SP 12



SELF PROPELLED TESTS
SP 12

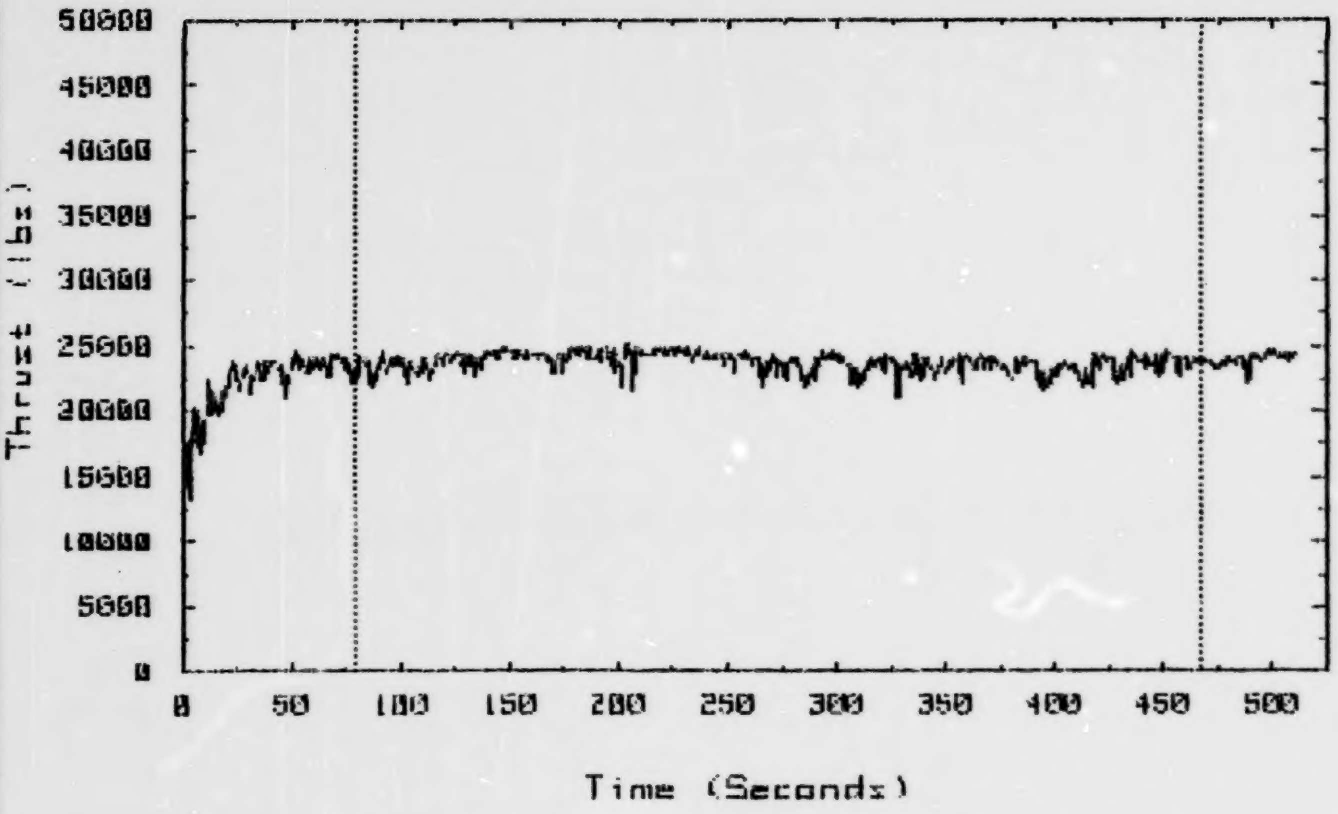


SELF PROPELLED TESTS
SP 12

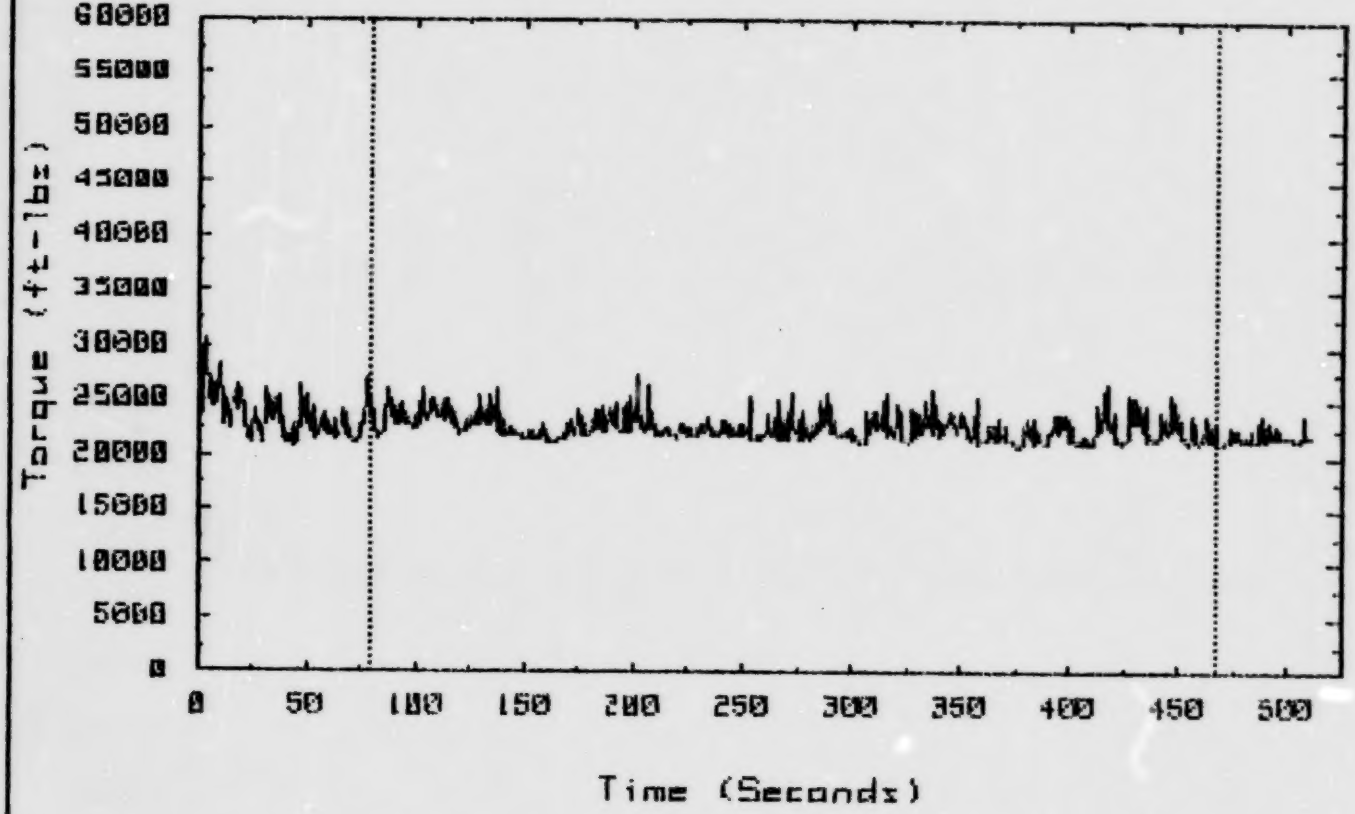


SELF PROPELLED TESTS
SP 12

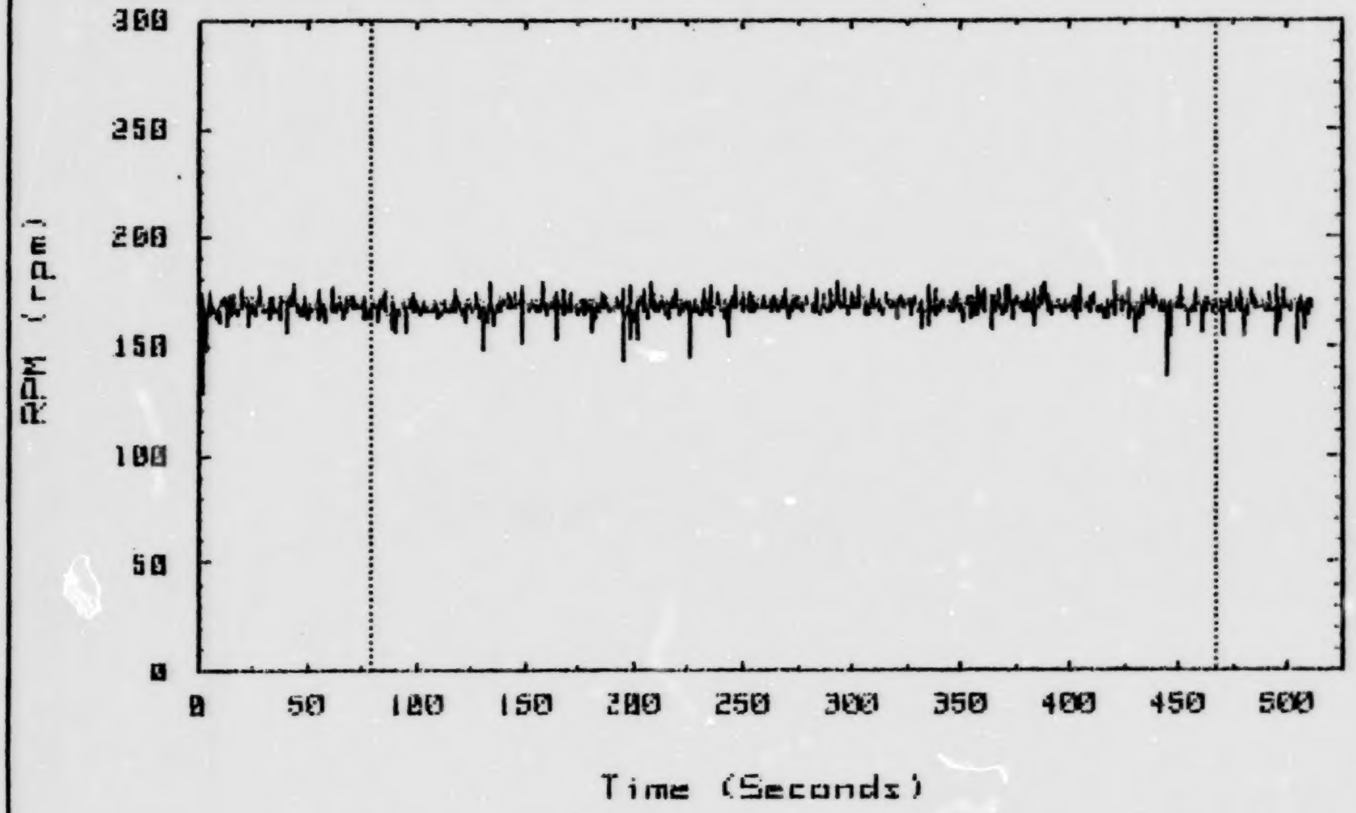
```
              Test Results for Test SP_13:  02/24/86, 08:45:37
              For the Interval Between  80  sec and  467  sec

   CHANNEL                          MAXIMUM     MINIMUM      MEAN     STDRD DEV

 1  Thrust (lbs)                    25196.1     21128.5    23825.9      652.1
 2  Torque (ft-lbs)                 27321.0     20875.9    22565.6     1009.6
 3  RPM (rpm)                         179.0       135.7      168.7        3.0
 4  Ship Speed (kts)                    4.2         2.1        3.2         .3
 6  Shaft Horsepower                  858.1       599.9      724.8       32.4


              Test Results for Test SP_13:  02/24/86, 08:45:37
              For the Interval Between  80  sec and  467  sec

             Average Ship Speed                    3.2   kts
             Average Thrust                    23825.9   lbs
             Average Torque                    22565.6   ft-lbs
             Average RPM                         168.7   RPM
             Average Shaft Horsepower            724.9   HP
             Average Ice Thickness              1.0833   ft
             Mean Advance Coeff., Js            0.2277
             Thrust Coefficient, Kt             2.976E-01
             Torque Coefficient, Kq             3.315E-02

------------------------------------------------------------------------------

                          RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs         1.732E+04                      1.629E+04
Thrust Deduction             2.732E-01                      3.164E-01
Propulsive Coeff.            2.364E-01                      2.223E-01

------------------------------------------------------------------------------

                            Thrust Identity                 Torque Identity

Advance Coefficient           -0.0434                        0.0239
Thrust Coefficient             2.976E-01                     2.765E-01
Torque Coefficient             3.563E-02                     3.315E-02
Advance Velocity,fps          -1.04                           .57
Effective Wake                 1.191E+00                     8.951E-01
Open Prop Eff.                -5.767E-02                     3.173E-02
Relative Rotative Eff          1.075E+00                     1.076E+00
Hull Efficiency (Res. Form 1) -3.815E+00                     5.929E+00
Hull Efficiency (Res. Form 2) -3.588E+00                     6.516E+00
```



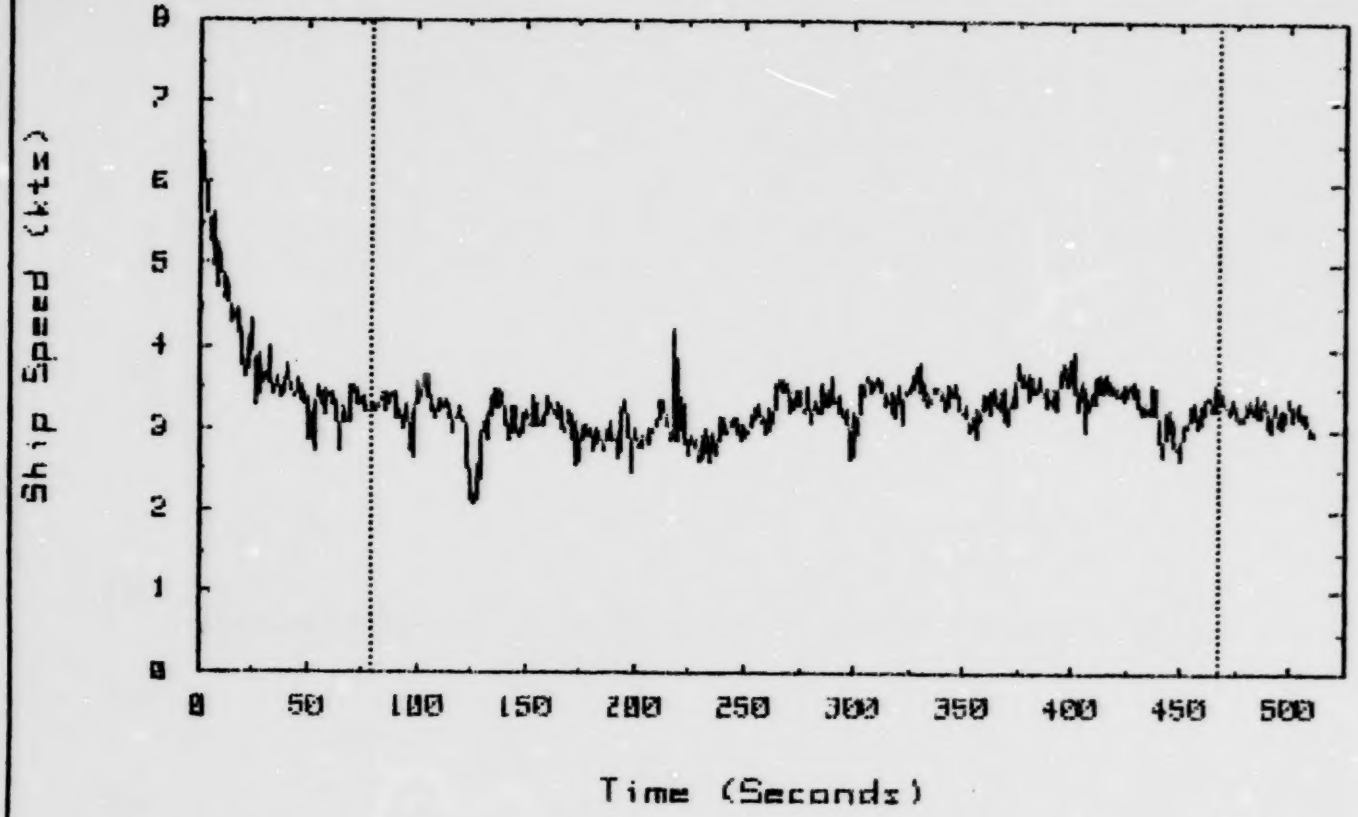
SELF PROPELLED TESTS
SP 13



SELF PROPELLED TESTS
SP 13

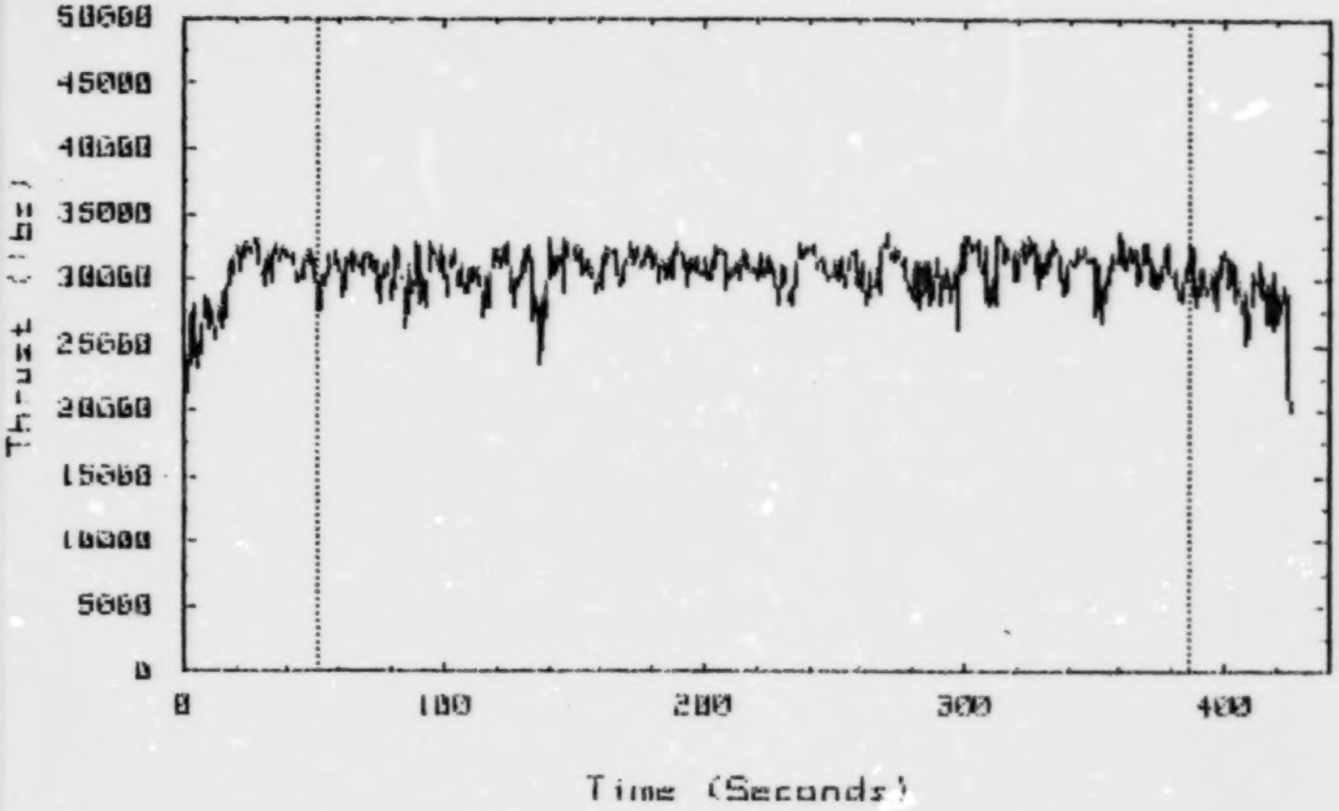


SELF PROPELLED TESTS
SP 13

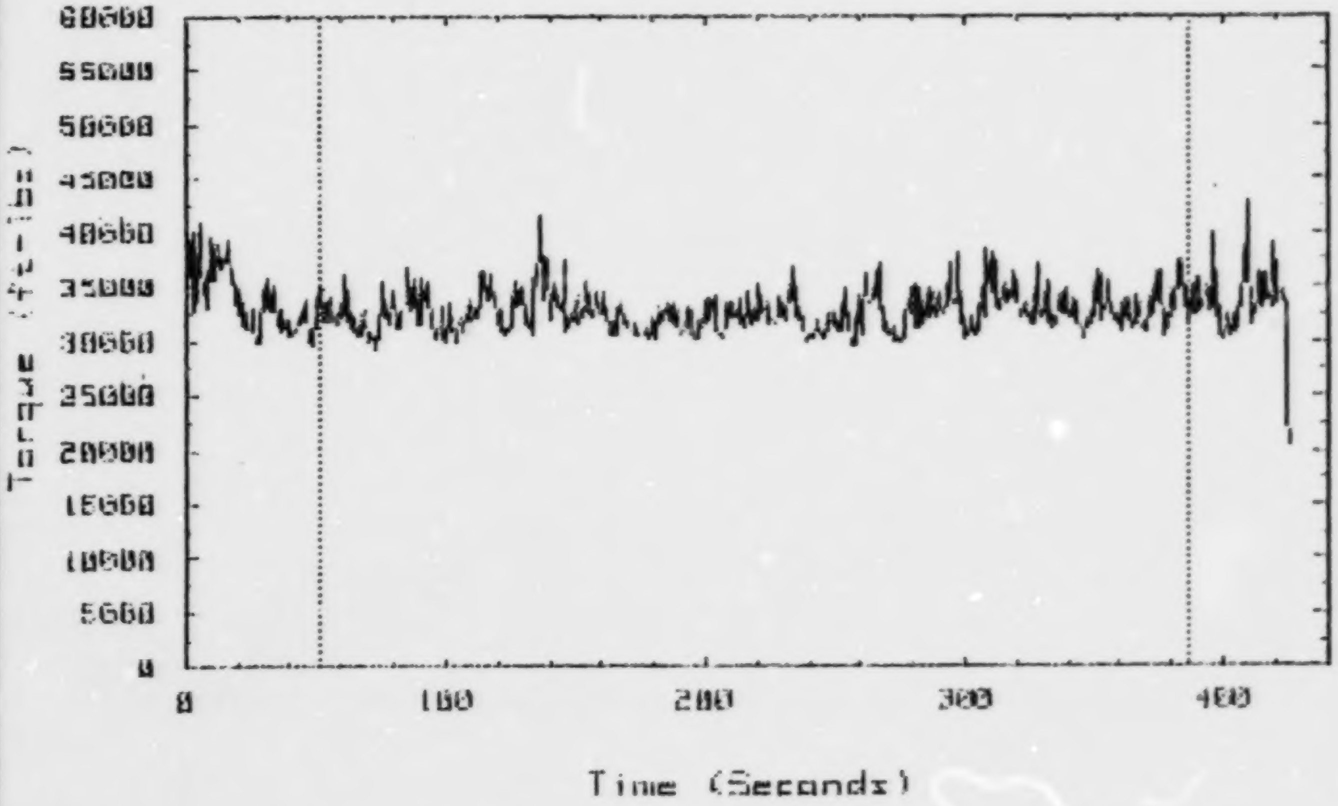


SELF PROPELLED TESTS
SP 13

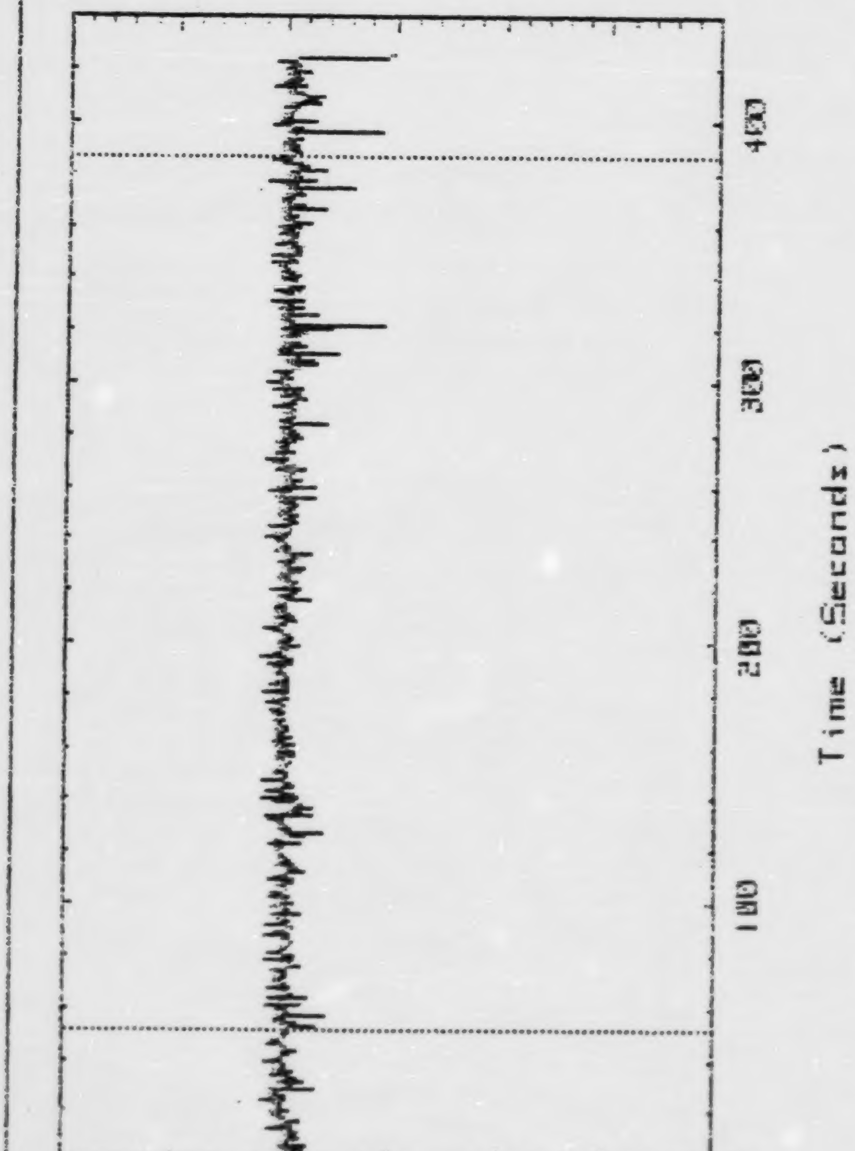
```
                  Test Results for Test SP_14:  02/24/86, 09:09:50
                  For the Interval Between  51  sec and  386  sec

  CHANNEL                                MAXIMUM      MINIMUM      MEAN       STDRD DEV

 1  Thrust (lbs)                         33615.1      23635.3     30904.5      1271.4
 2  Torque (ft-lbs)                      41548.4      29219.8     32745.3      1637.0
 3  RPM (rpm)                              208.7        155.0       198.2         3.7
 4  Ship Speed (kts)                         5.7          3.4         4.5          .3
 6  Shaft Horsepower                      1483.9        977.5      1235.0        58.0


                  Test Results for Test SP_14:  02/24/86, 09:09:50
                  For the Interval Between  51  sec and  386  sec

                 Average Ship Speed                 4.5   kts
                 Average Thrust                 30904.5   lbs
                 Average Torque                 32745.3   ft-lbs
                 Avarage RPM                      198.2   RPM
                 Average Shaft Horsepower        1235.0   HP
                 Average Ice Thickness           1.0833   ft
                 Mean Advance Coeff., Js         0.2702
                 Thrust Coefficient, Kt          2.798E-01
                 Torque Coefficient, Kq          3.488E-02

---------------------------------------------------------------------------------

                        RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs        2.173E+04                       2.081E+04
Thrust Deduction            2.963E-01                       3.267E-01
Propulsive Coeff.           2.429E-01                       2.323E-01

---------------------------------------------------------------------------------

                         Thrust Identity                 Torque Identity

Advance Coefficient          0.0135                       -0.0255
Thrust Coefficient          2.792E-01                      2.920E-01
Torque Coefficient          3.351E-02                      3.486E-02
Advance Velocity,fps         .38                           -.72
Effective Wake              9.502E-01                      1.094E+00
Open Prop Eff.              1.768E-02                     -3.389E-02
Relative Rotative Eff       9.607E-01                      9.531E-01
Hull Efficiency (Res. Form 1)  1.412E+01                  -7.457E+00
Hull Efficiency (Res. Form 2)  1.352E+01                  -7.141E+00
```



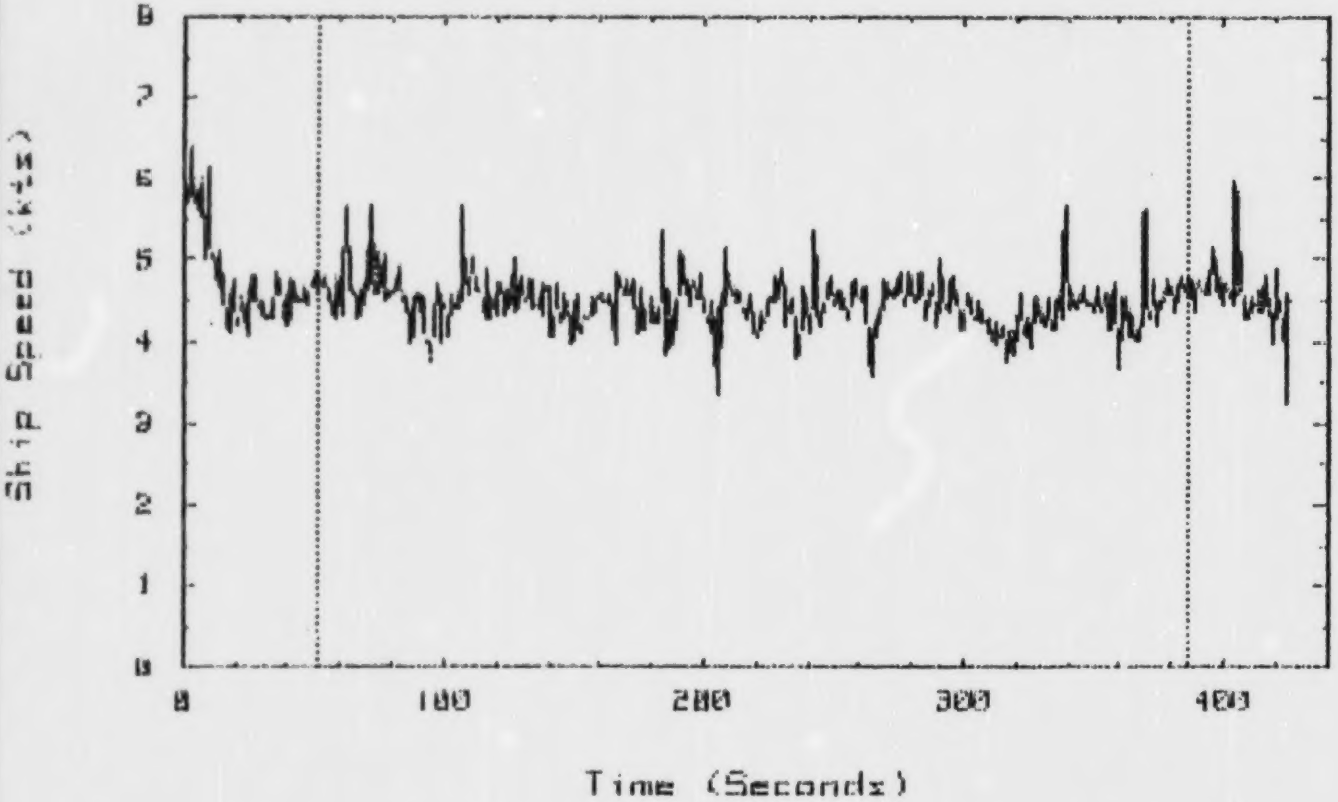
SELF PROPELLED TESTS
SP 14



SELF PROPELLED TESTS
SP 14

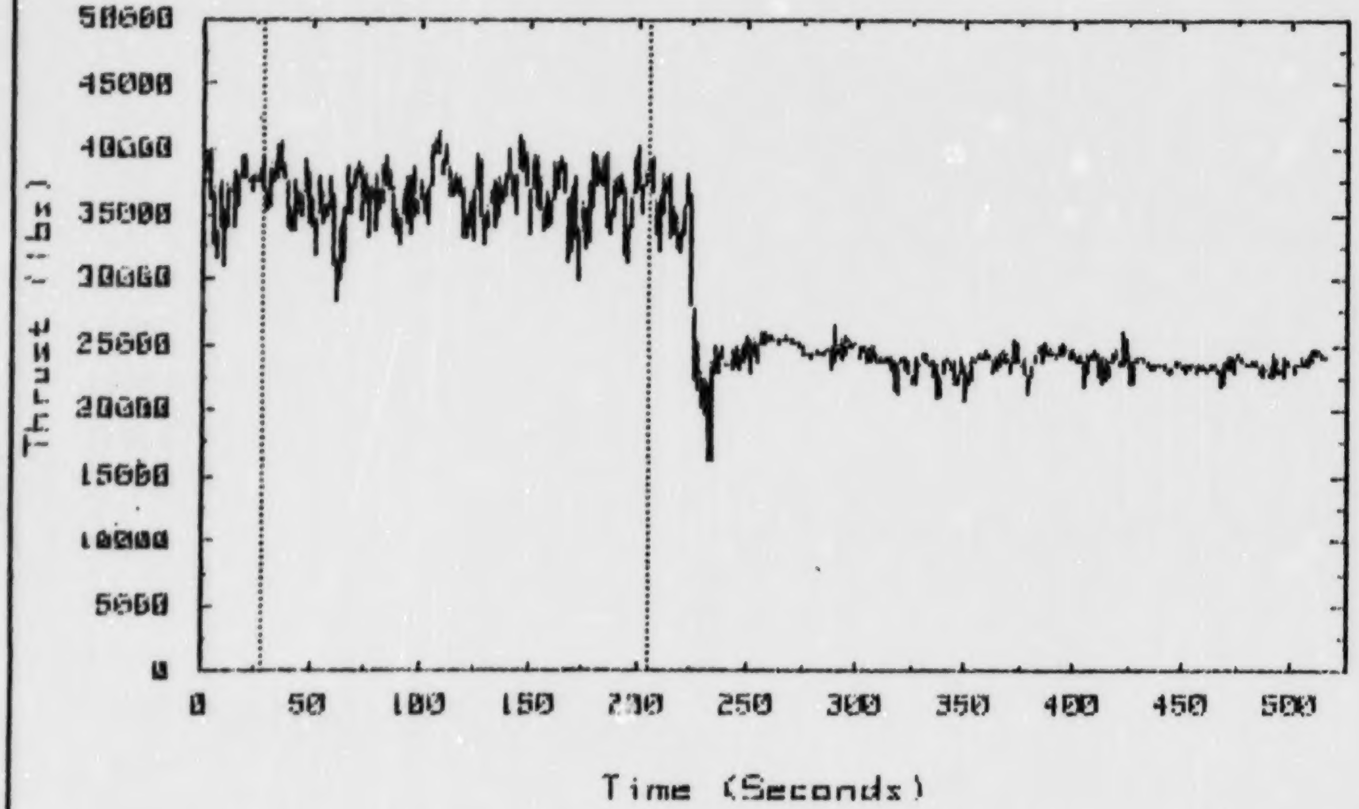


SELF PROPELLED TESTS
SP 14

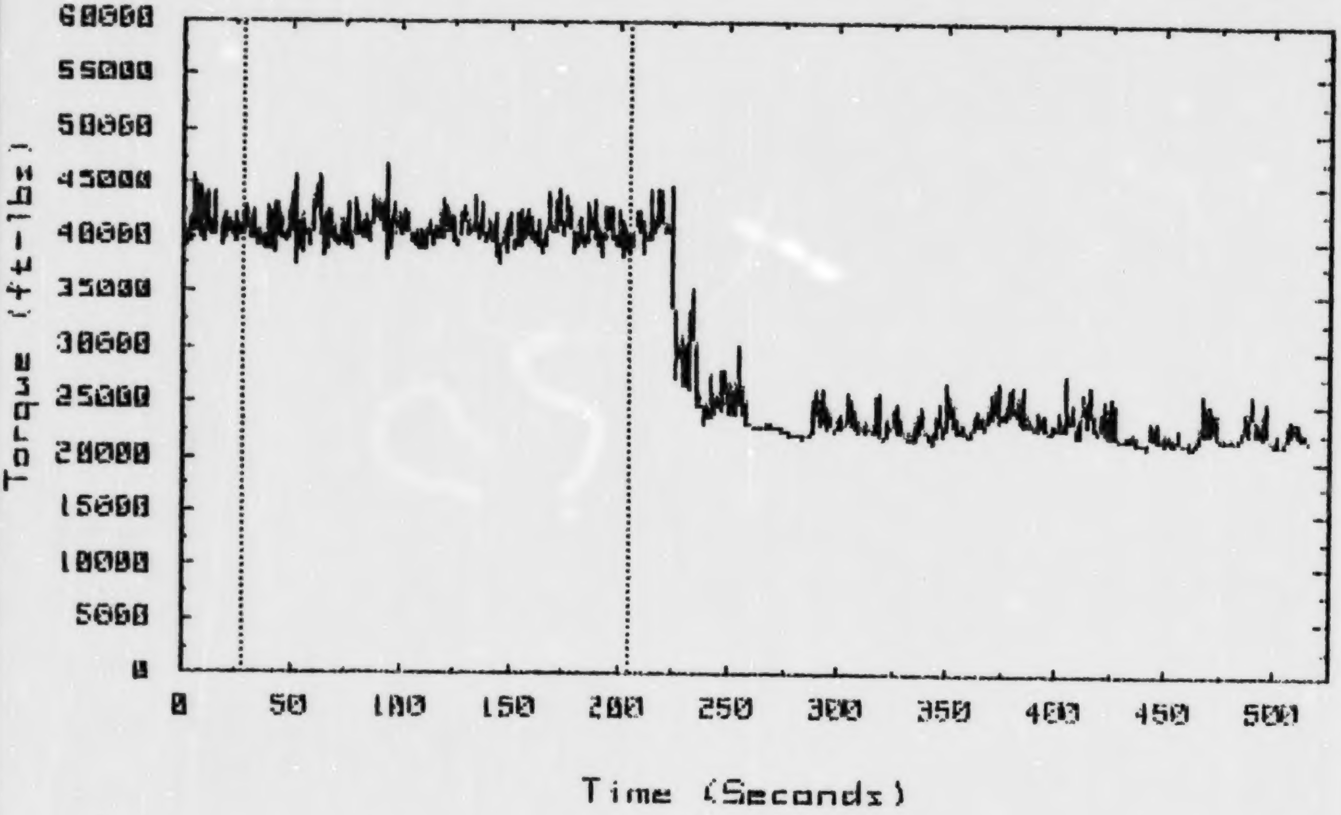


SELF PROPELLED TESTS
SP 14

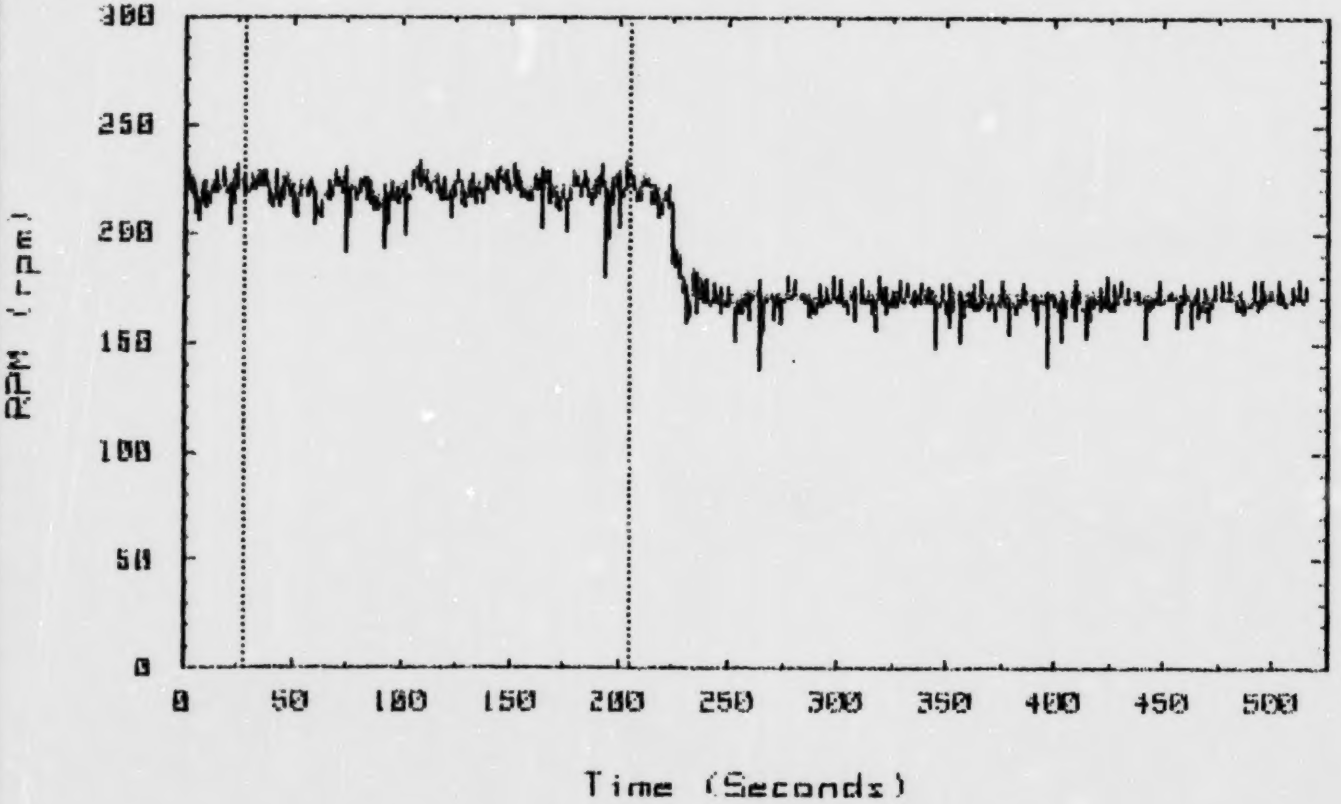
```
              Test Results for Test SP_15A:  02/24/86, 10:20:33
              For the Interval Between  28  sec and  205  sec

   CHANNEL                              MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                        41371.9     28365.0     36594.1      2130.5
 2  Torque (ft-lbs)                     46790.0     37617.1     40906.1      1268.5
 3  RPM (rpm)                             233.9       180.0       220.9         5.2
 4  Ship Speed (kts)                        6.3         4.2         5.3          .3
 6  Shaft Horsepower                     1920.9      1446.7      1719.7        46.0


              Test Results for Test SP_15A:  02/24/86, 10:20:33
              For the Interval Between  28  sec and  205  sec

            Average Ship Speed                5.3   kts
            Average Thrust                36594.1   lbs
            Average Torque                40906.1   ft-lbs
            Average RPM                     220.9   RPM
            Average Shaft Horsepower       1719.7   HP
            Average Ice Thickness          1.4167   ft
            Mean Advance Coeff., Js        0.2946
            Thrust Coefficient, Kt         2.666E-01
            Torque Coefficient, Kq         3.506E-02

-------------------------------------------------------------------------------

                           RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs          3.385E+04                      2.869E+04
Thrust Deduction              7.493E-02                      2.161E-01
Propulsive Coeff.             3.186E-01                      2.700E-01

-------------------------------------------------------------------------------

                            Thrust Identity                Torque Identity

Advance Coefficient           0.0946                        -0.0307
Thrust Coefficient            2.666E-01                      2.937E-01
Torque Coefficient            3.202E-02                      3.506E-02
Advance Velocity,fps          1.71                          -.96
Effective Wake                8.081E-01                      1.108E+00
Open Prop Eff.                7.238E-02                     -4.089E-02
Relative Rotative Eff         9.133E-01                      9.079E-01
Hull Efficiency (Res. Form 1) 4.919E+00                     -9.562E+00
Hull Efficiency (Res. Form 2) 4.064E+00                     -7.256E+00
```



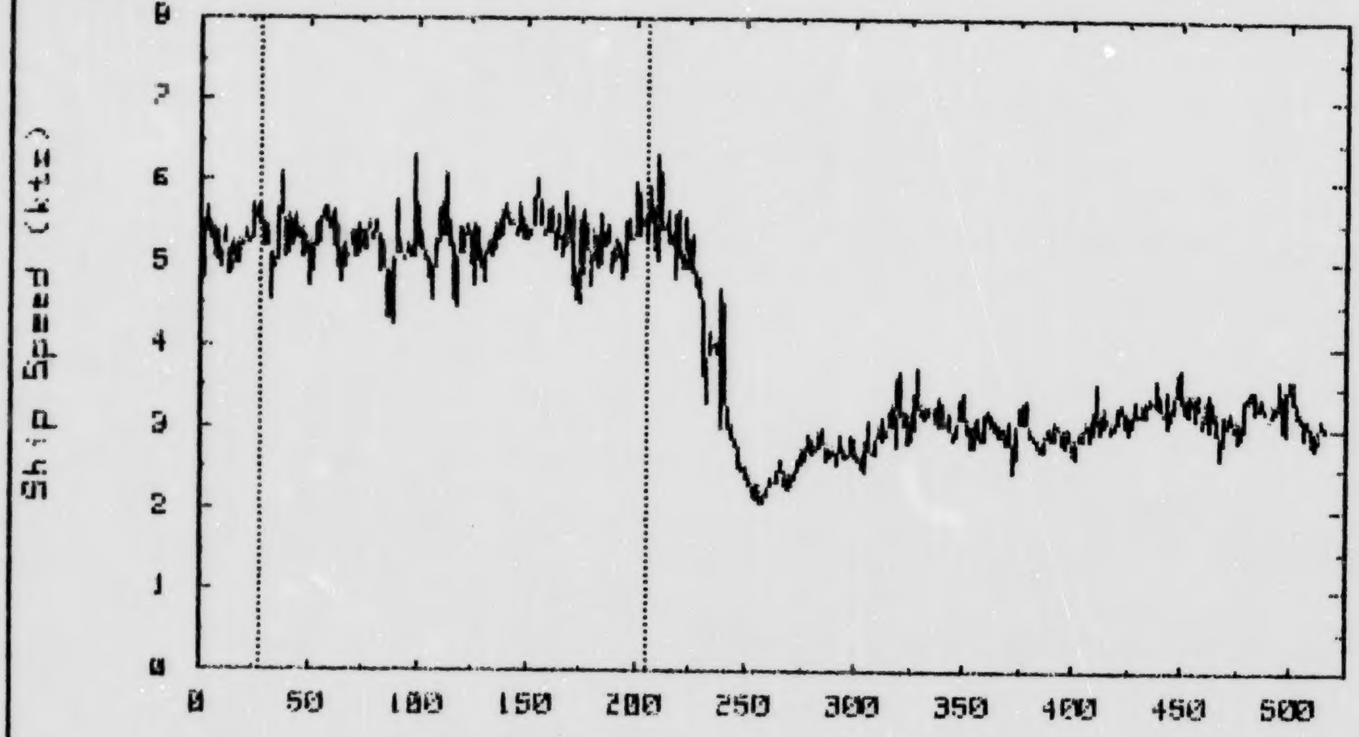
SELF PROPELLED TESTS
SP 15



SELF PROPELLED TESTS
SP 15

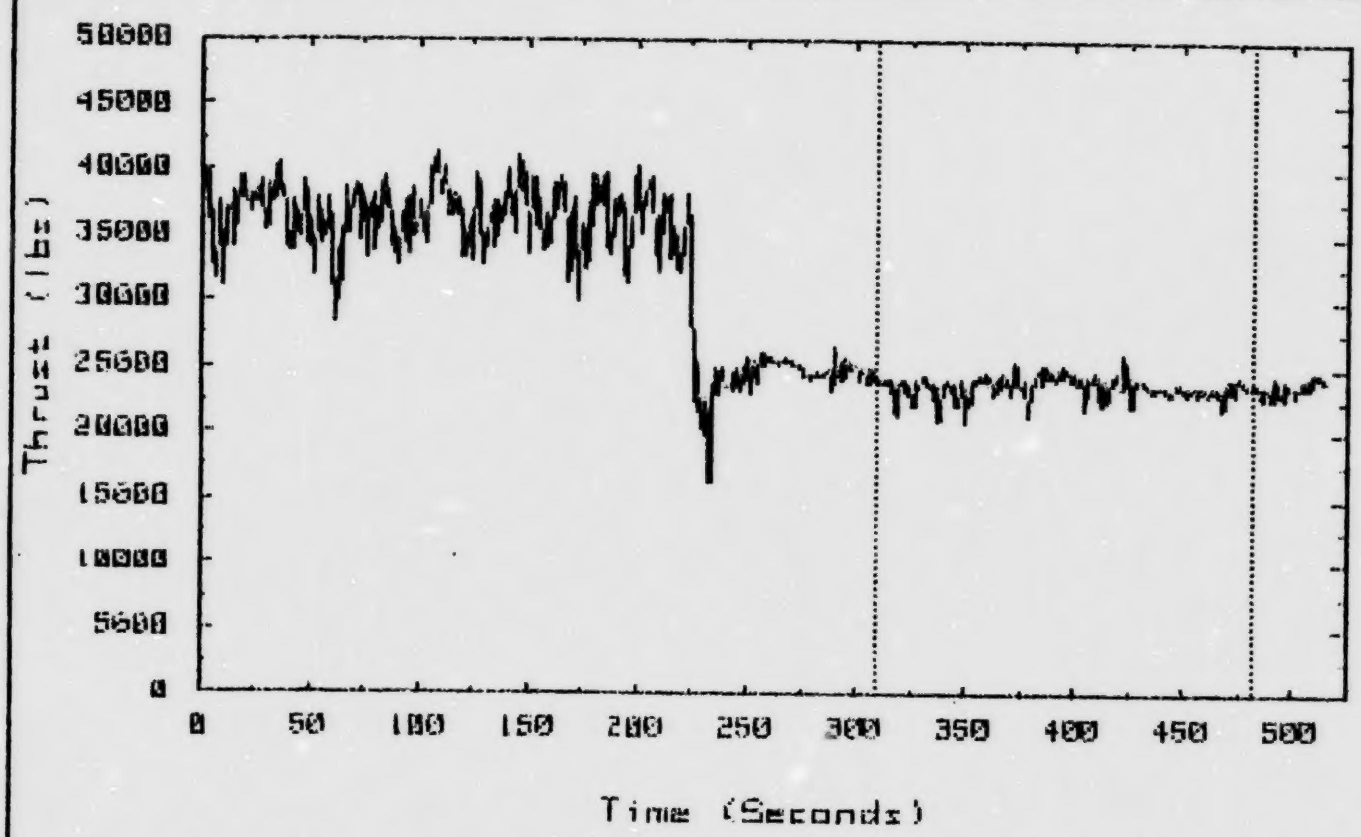


SELF PROPELLED TESTS
SP 15

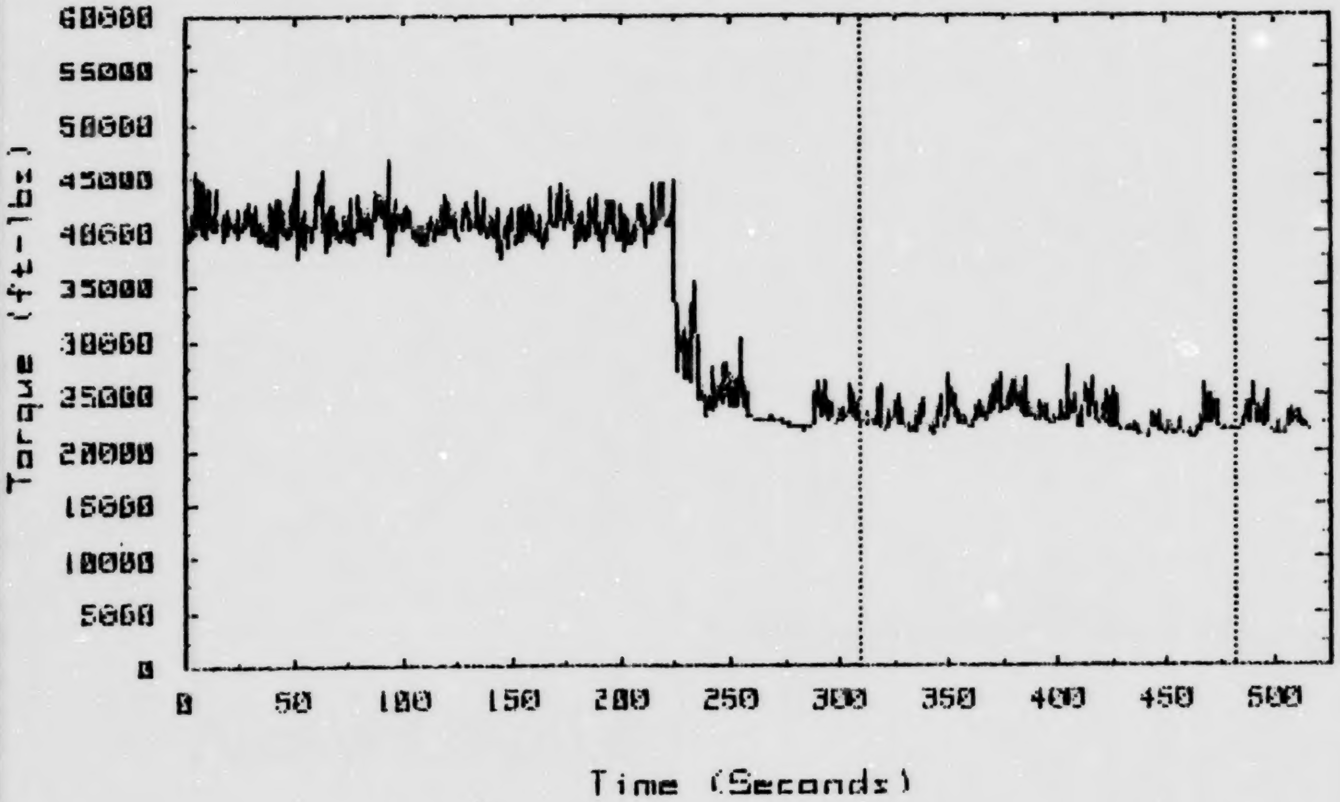


SELF PROPELLED TESTS
SP 15

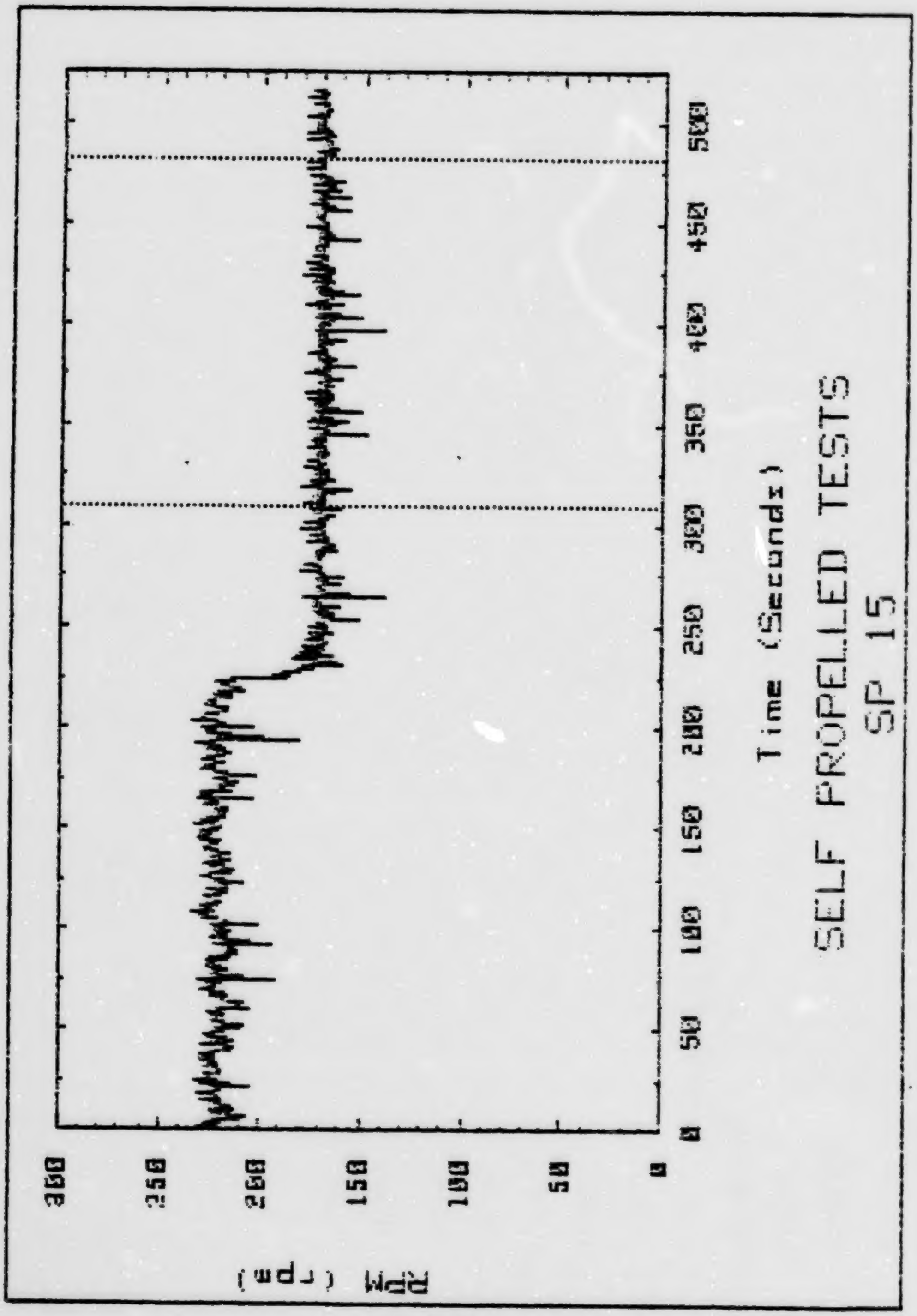
```
              Test Results for Test SP_158:  02/24/86, 10:20:33
              For the Interval Between  309  sec and  482  sec

  CHANNEL                               MAXIMUM     MINIMUM      MEAN      STDRD DEV

 1  Thrust (lbs)                        25856.3     20892.0    23728.0       841.1
 2  Torque (ft-lbs)                     27508.2     21170.1    23017.3      1160.4
 3  RPM (rpm)                             180.7       139.4      170.4         3.4
 4  Ship Speed (kts)                        3.7         2.5        3.1          .2
 6  Shaft Horsepower                      887.2       600.9      746.6        37.0


              Test Results for Test SP_158:  02/24/86, 10:20:33
              For the Interval Between  309  sec and  482  sec

             Average Ship Speed                  3.1     kts
             Average Thrust                  23728.0     lbs
             Average Torque                  23017.9     ft-lbs
             Average RPM                       170.4     RPM
             Average Shaft Horsepower          746.6     HP
             Average Ice Thickness            1.2500     ft
             Mean Advance Coeff., Js          0.2171
             Thrust Coefficient, Kt          2.905E-01
             Torque Coefficient, Kq          3.316E-02

--------------------------------------------------------------------------------

                            RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs           2.033E+04                      1.891E+04
Thrust Deduction               1.431E-01                      2.031E-01
Propulsive Coeff.              2.594E-01                      2.412E-01

--------------------------------------------------------------------------------

                              Thrust Identity                Torque Identity

Advance Coefficient            -0.0207                        0.0239
Thrust Coefficient              2.905E-01                     2.765E-01
Torque Coefficient              3.477E-02                     3.316E-02
Advance Velocity,fps           -.50                            .58
Effective Wake                  1.095E+00                     9.901E-01
Open Prop Eff.                 -2.747E-02                     3.170E-02
Relative Rotative Eff           1.049E+00                     1.051E+00
Hull Efficiency (Res. Form 1)  -9.007E+00                     7.794E+00
Hull Efficiency (Res. Form 2)  -8.376E+00                     7.248E+00
```



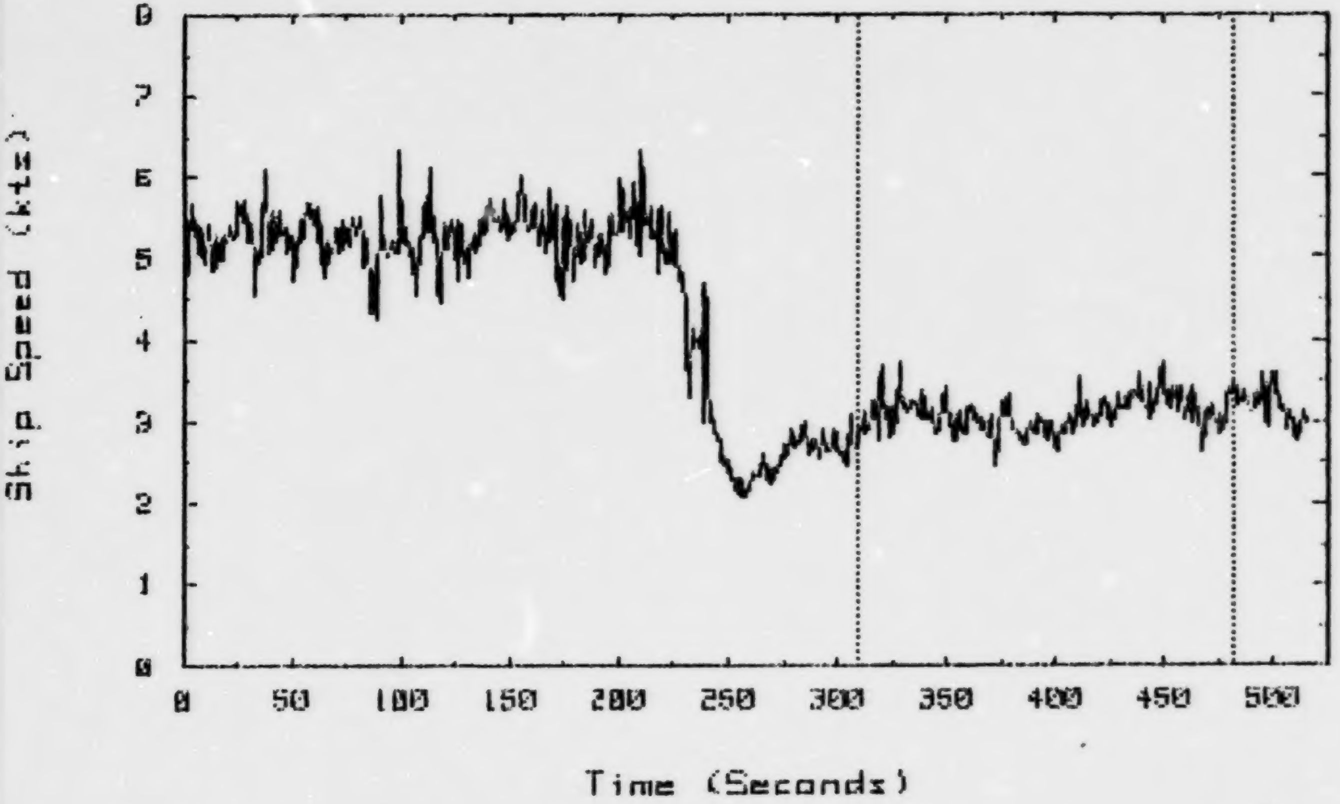
SELF PROPELLED TESTS
SP 15



SELF PROPELLED TESTS
SP 15

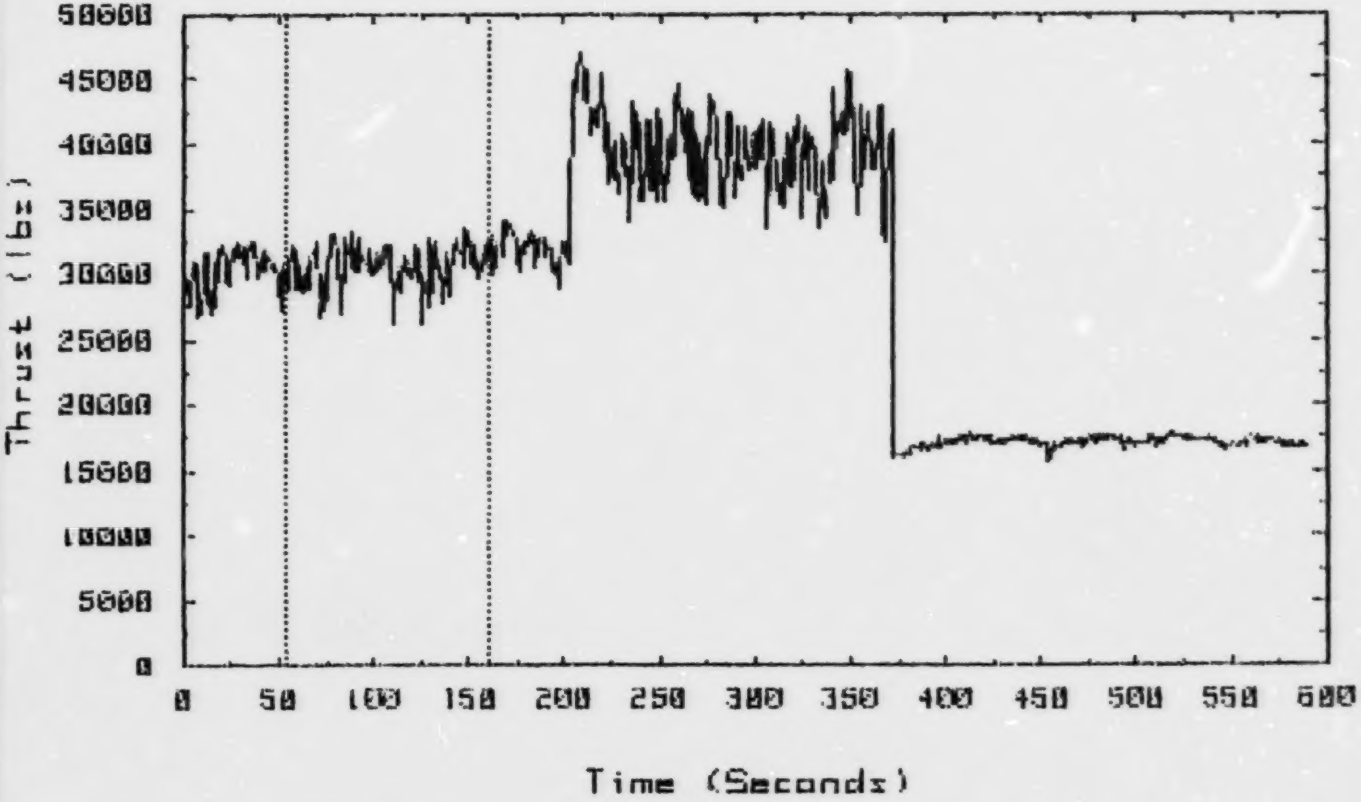


SELF PROPELLED TESTS
SP 15

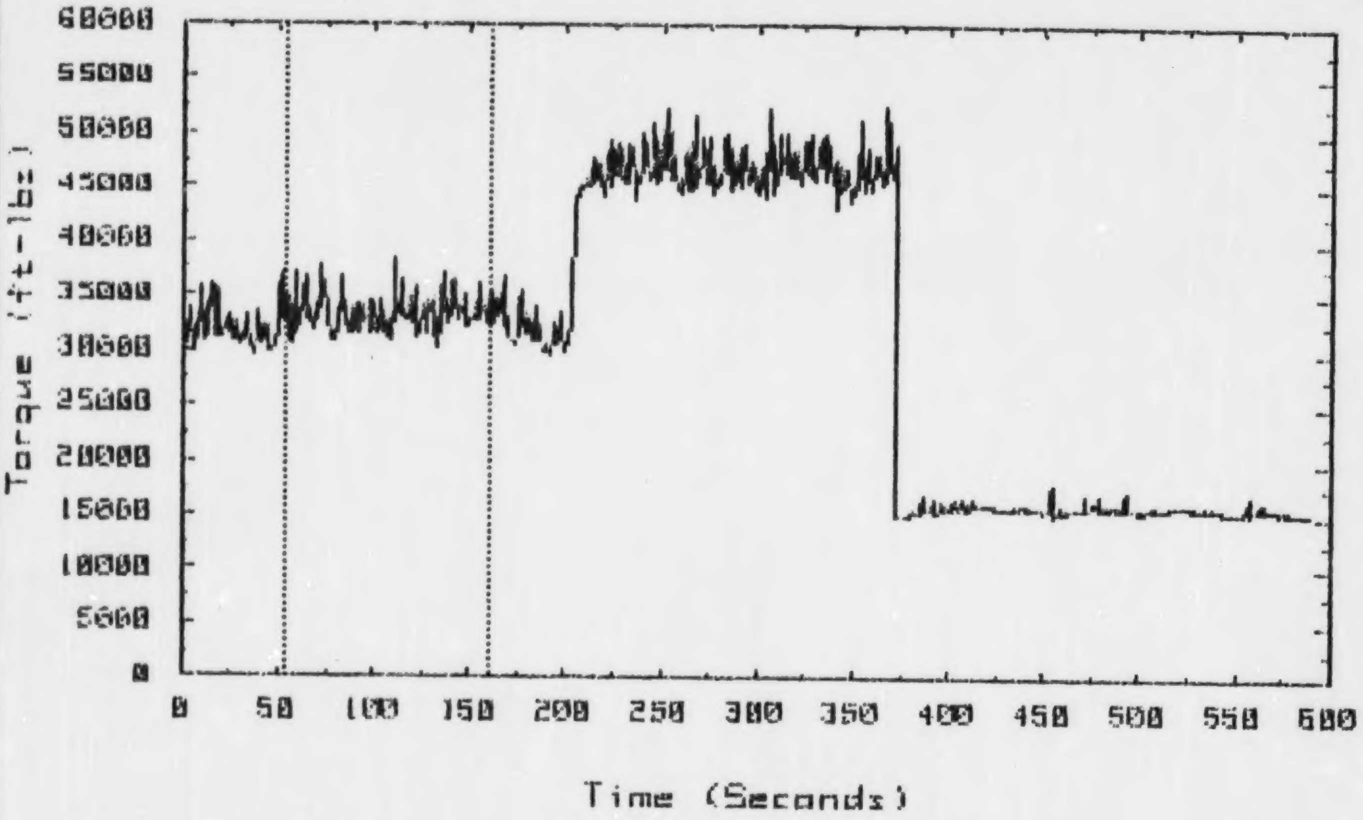


SELF PROPELLED TESTS
SP 15

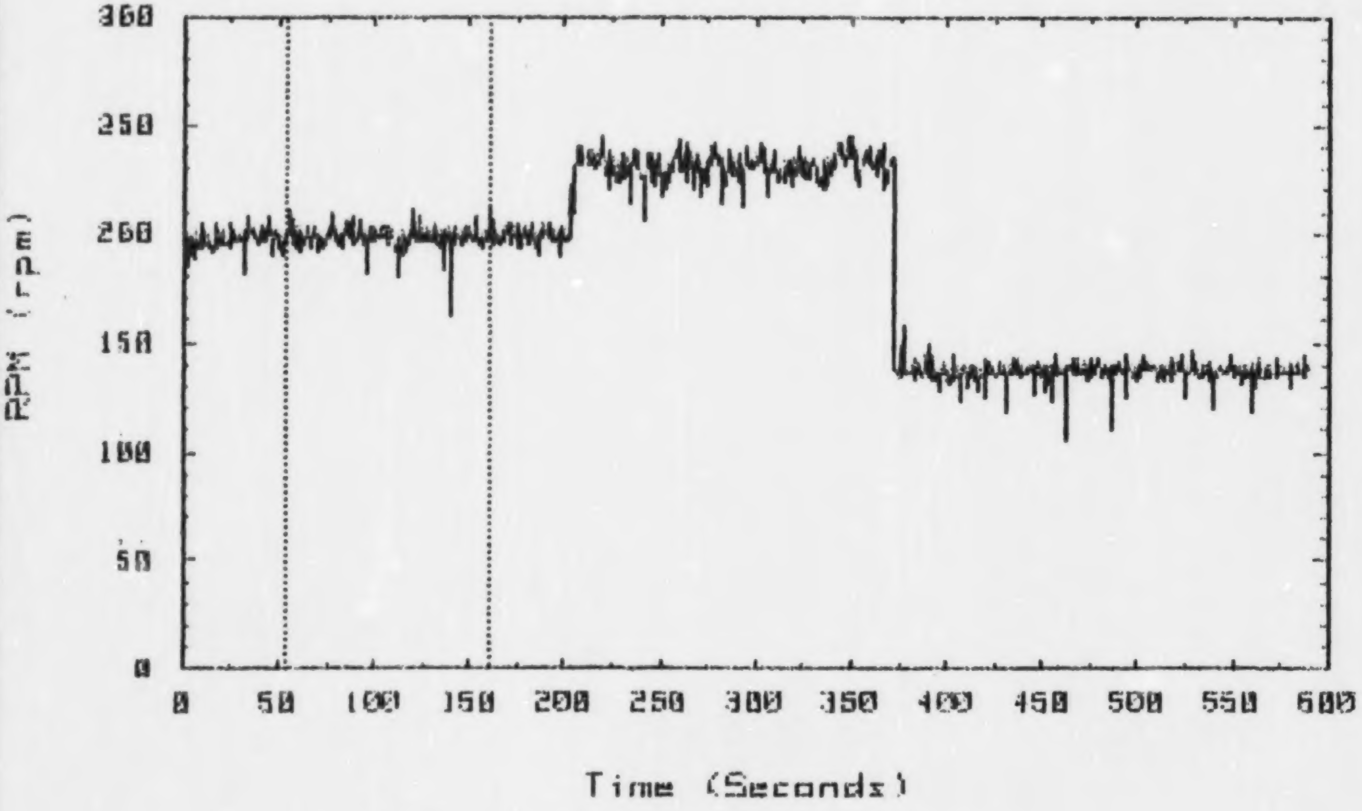
```
             Test Results for Test SP_16A:  02/24/86, 10:42:54
             For the Interval Between  54  sec and  161  sec

   CHANNEL                          MAXIMUM     MINIMUM      MEAN     STDPD DEV

 1  Thrust (lbs)                    33615.1     26142.1     30850.5     1263.3
 2  Torque (ft-lbs)                 38259.0     30316.2     33354.4     1311.6
 3  RPM (rpm)                         211.2       163.2       199.1        3.7
 4  Ship Speed (kts)                    5.3         3.7         4.3         .2
 5  Shaft Horsepower                 1405.7      1106.3      1264.0       46.9


             Test Results for Test SP_16A:  02/24/86, 10:42:54
             For the Interval Between  54  sec and  161  sec

            Average Ship Speed                   4.3    kts.
            Average Thrust                   30850.5    lbs
            Average Torque                   33354.4    ft-lbs
            Average RPM                        199.1    RPM
            Average Shaft Horsepower          1264.0    HP
            Average Ice Thickness             1.2500    ft
            Mean Advance Coeff., Js           0.2571
            Thrust Coefficient, Kt            2.767E-01
            Torque Coefficient, Kq            3.520E-02

-----------------------------------------------------------------------------

                        RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs       2.507E+04                      2.230E+04
Thrust Deduction           1.974E-01                      2.773E-01
Propulsive Coeff.          2.615E-01                      2.325E-01

-----------------------------------------------------------------------------

                          Thrust Identity                Torque Identity

Advance Coefficient         0.0232                        -0.0345
Thrust Coefficient          2.767E-01                      2.948E-01
Torque Coefficient          3.315E-02                      3.520E-02
Advance Velocity,fps         .65                          -.97
Effective Wake              9.099E-01                      1.134E+00
Open Prop Eff.              3.078E-02                     -4.593E-02
Relative Rotative Eff       9.419E-01                      9.395E-01
Hull Efficiency (Res. Form 1)  9.017E+00                  -6.049E+00
Hull Efficiency (Res. Form 2)  8.019E+00                  -5.379E+00
```



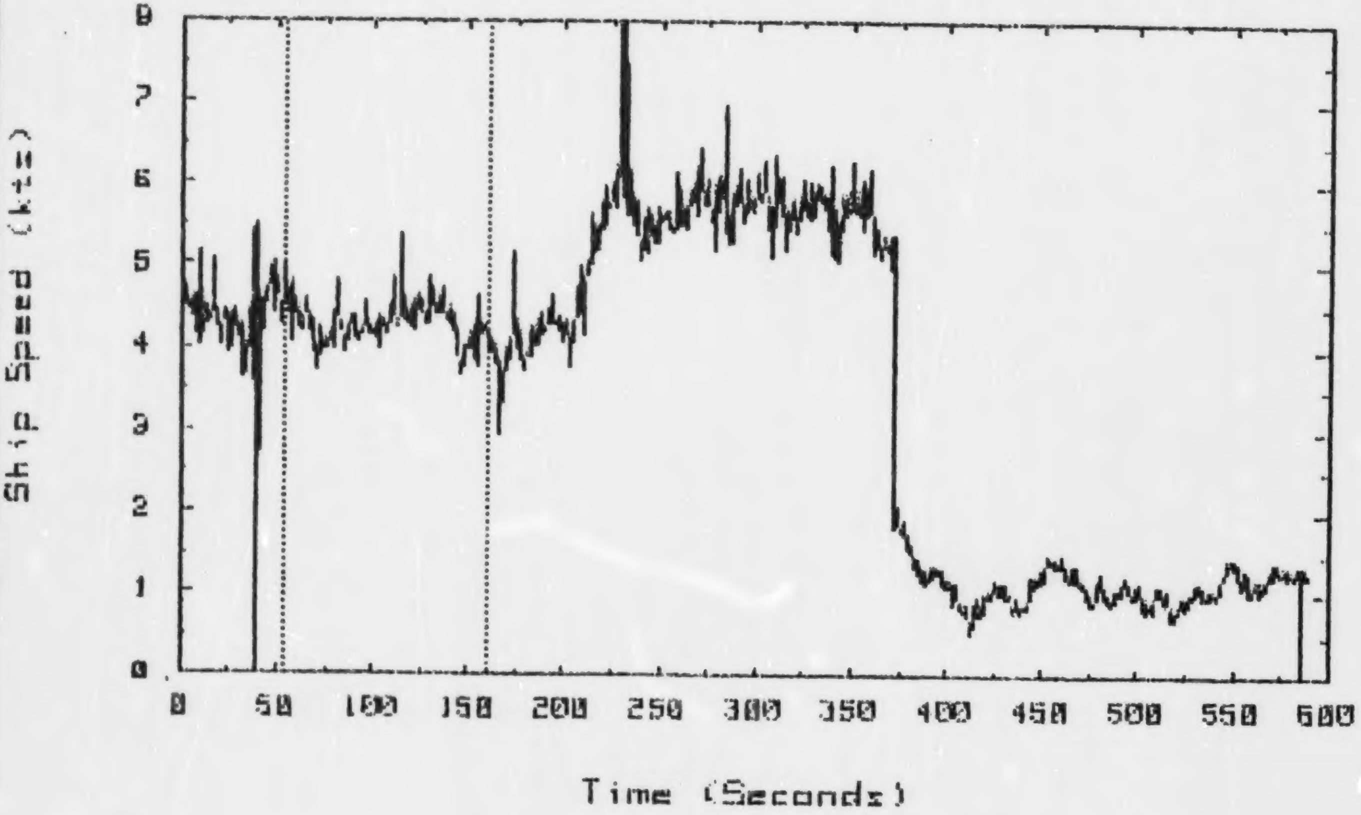
SELF PROPELLED TESTS
SP 16



SELF PROPELLED TESTS
SP 16

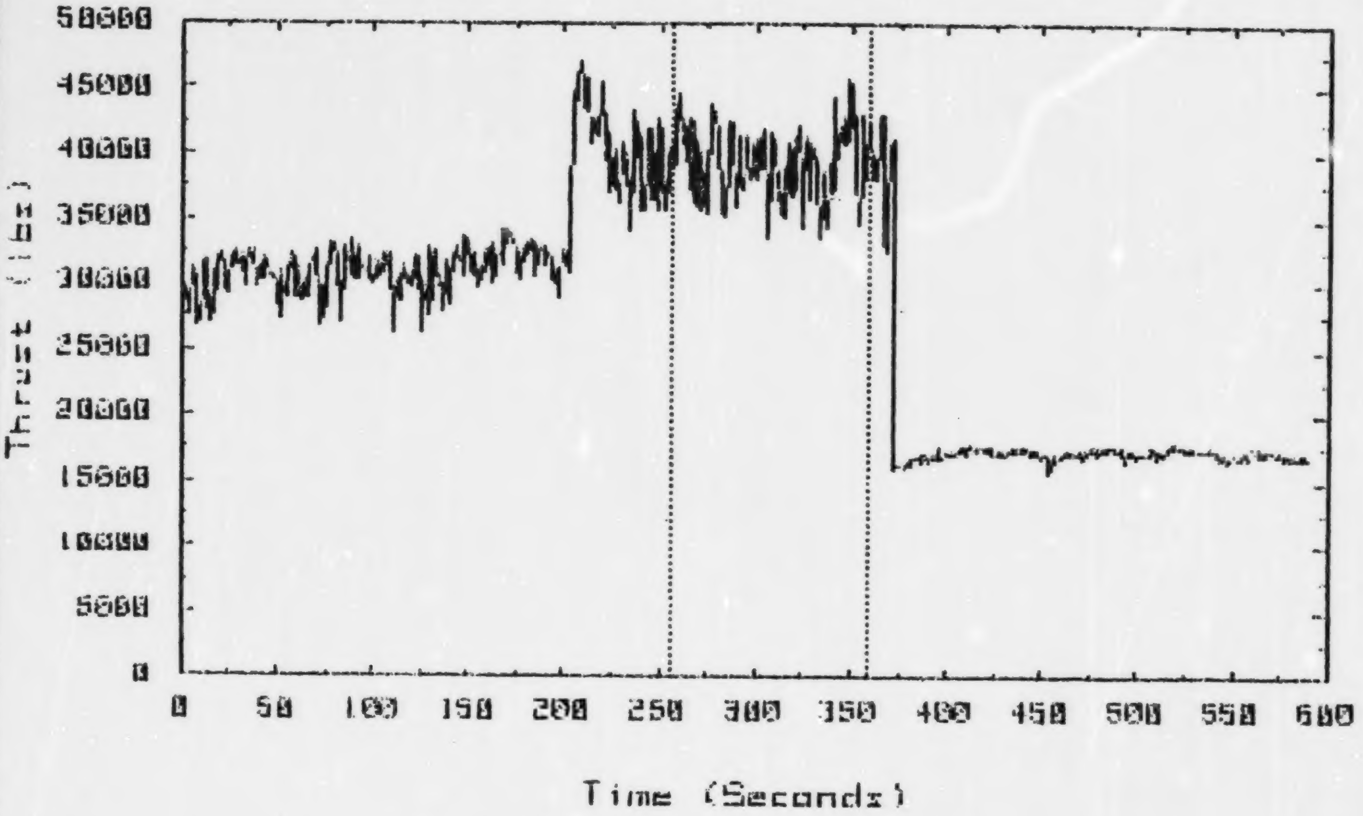


SELF PROPELLED TESTS
SP 16

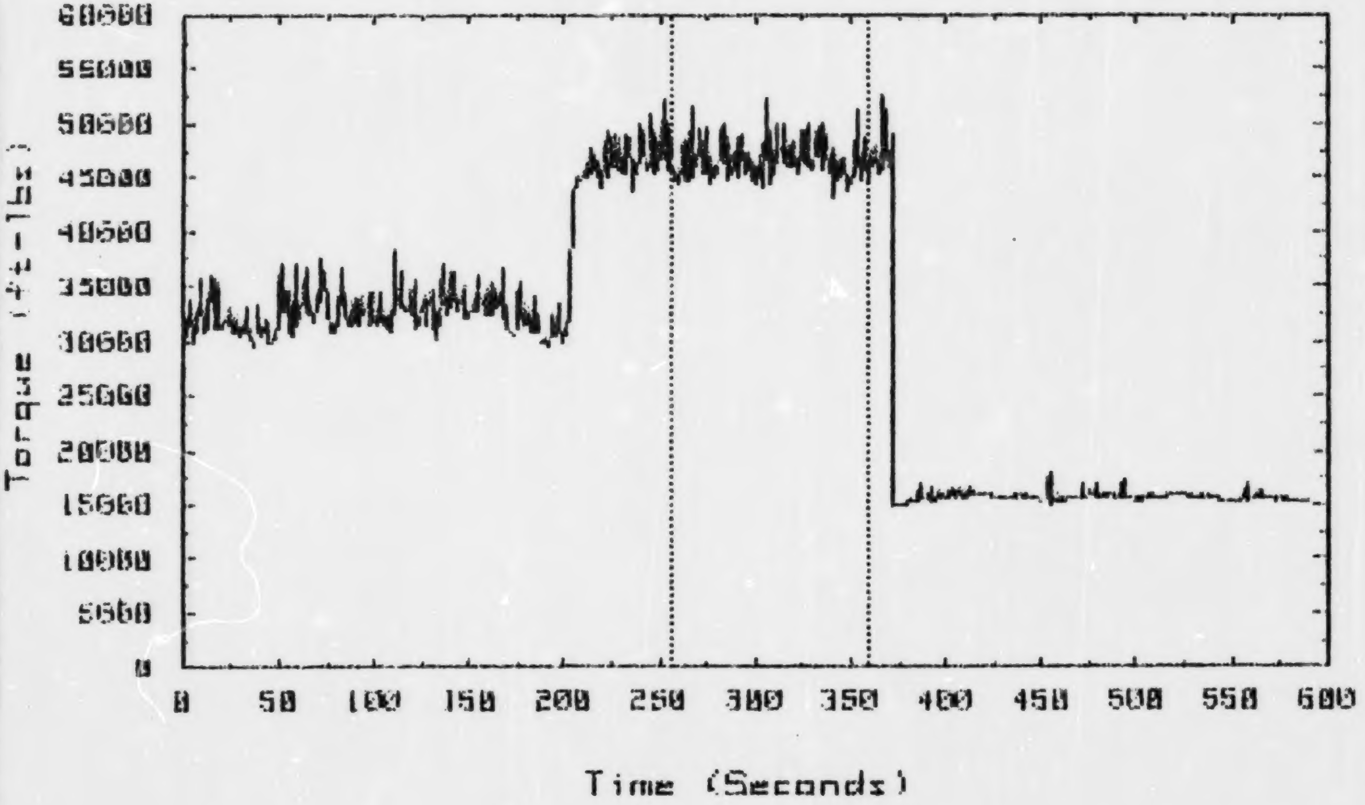


SELF PROPELLED TESTS
SP 16

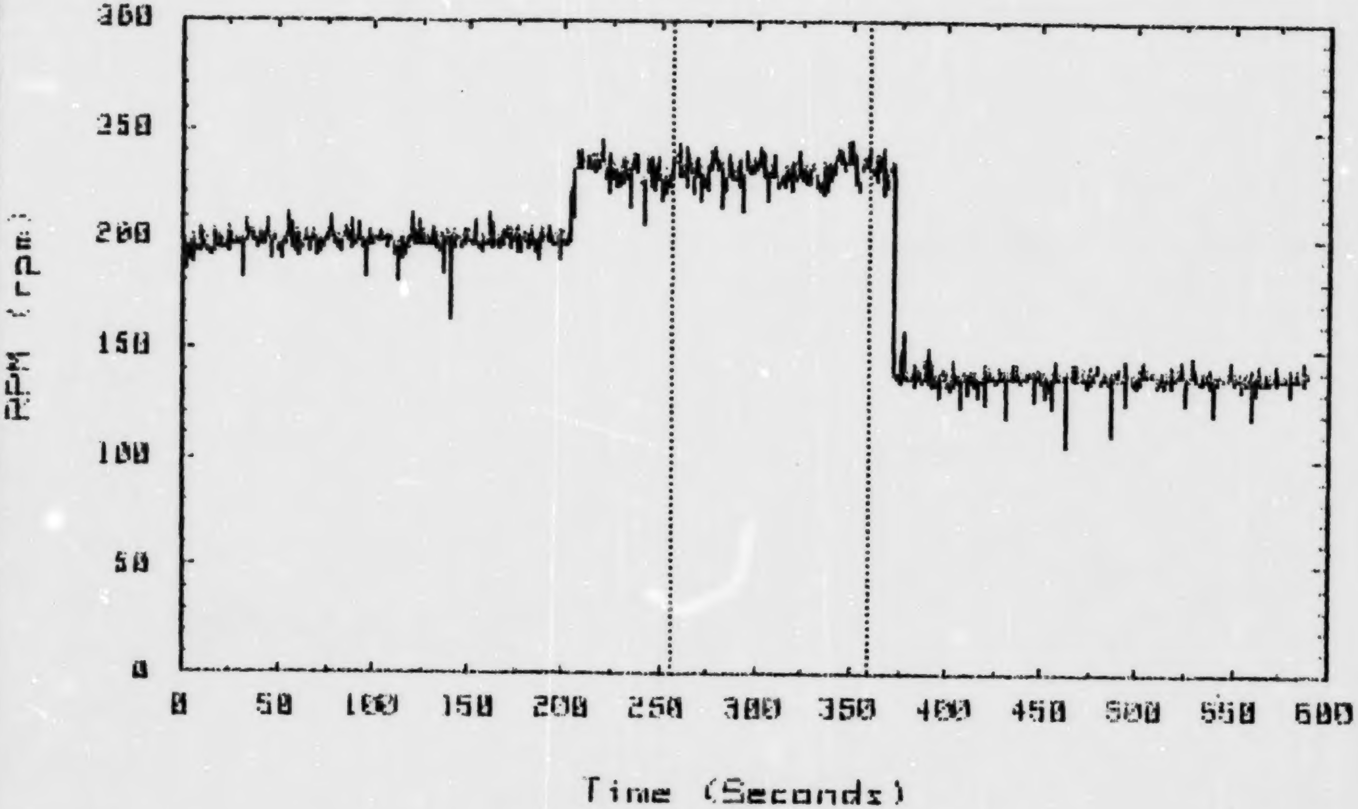
```
              Test Results for Test SP_168:  02/24/86, 10:42:54
              For the Interval Between  257  sec and  360  sec

  CHANNEL                             MAXIMUM     MINIMUM      MEAN     STDRD DEV

 1  Thrust (lbs)                      45561.4     33473.2     39512.1     2498.3
 2  Torque (ft-lbs)                   52058.4     43233.2     46839.6     1427.9
 3  RPM (rpm)                           244.8       212.4       232.2        5.1
 4  Ship Speed (kts)                      7.0         5.1         5.8         .2
 6  Shaft Horsepower                   2237.7      1905.3      2069.4       44.8


              Test Results for Test SP_168:  02/24/86, 10:42:54
              For the Interval Between  257  sec and  360  sec

             Average Ship Speed                    5.8   kts
             Averaga Thrust                    39512.1   lbs
             Average Torque                    46839.5   ft-lbs
             Average RPM                         232.2   RPM
             Average Shaft Horsepower           2069.4   HP
             Average Ice Thickness              1.5000   ft
             Mean Advance Coeff., Js            0.2971
             Thrust Coefficient, Kt             2.606E-01
             Torqua Coefficient, Kq             3.635E-02

-------------------------------------------------------------------------------

                        RESISTANCE FORM 1                  RESISTANCE FORM 2

Total Resistance,lbs        3.888E+04                          3.223E+04
Thrust Deduction            1.590E-02                          1.344E-01
Propulsive Coeff.           3.337E-01                          2.766E-01

-------------------------------------------------------------------------------

                          Thrust Identity                    Torque Identity

Advance Coefficient         0.0731                            -0.0671
Thrust Coefficient          2.606E-01                          3.049E-01
Torque Coefficient          3.137E-02                          3.635E-02
Advance Velocity,fps        2.41                              -2.21
Effective Wake              7.539E-01                          1.226E+00
Open Prop Eff.              9.666E-02                         -3.905E-02
Relative Rotative Eff       8.631E-01                          5.549E-01
Hull Efficiency (Res. Form 1)  3.993E+00                      -4.360E+00
Hull Efficiency (Res. Form 2)  3.314E+00                      -3.614E+00
```



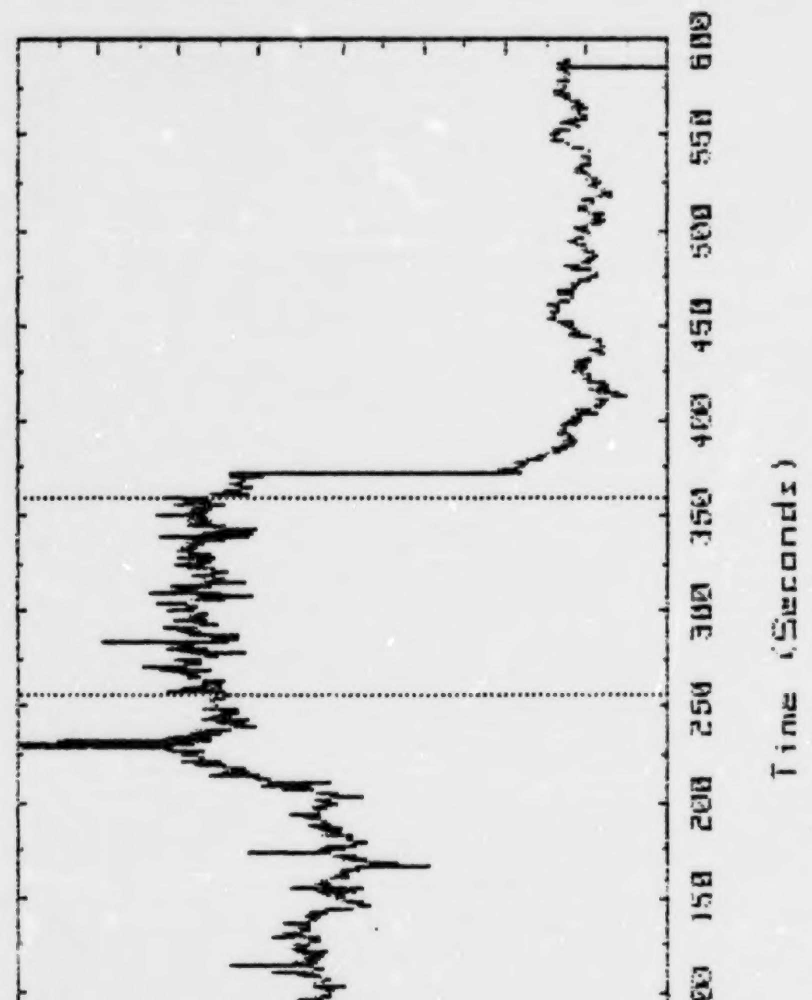
SELF PROPELLED TESTS
SP 16



SELF PROPELLED TESTS
SP 16

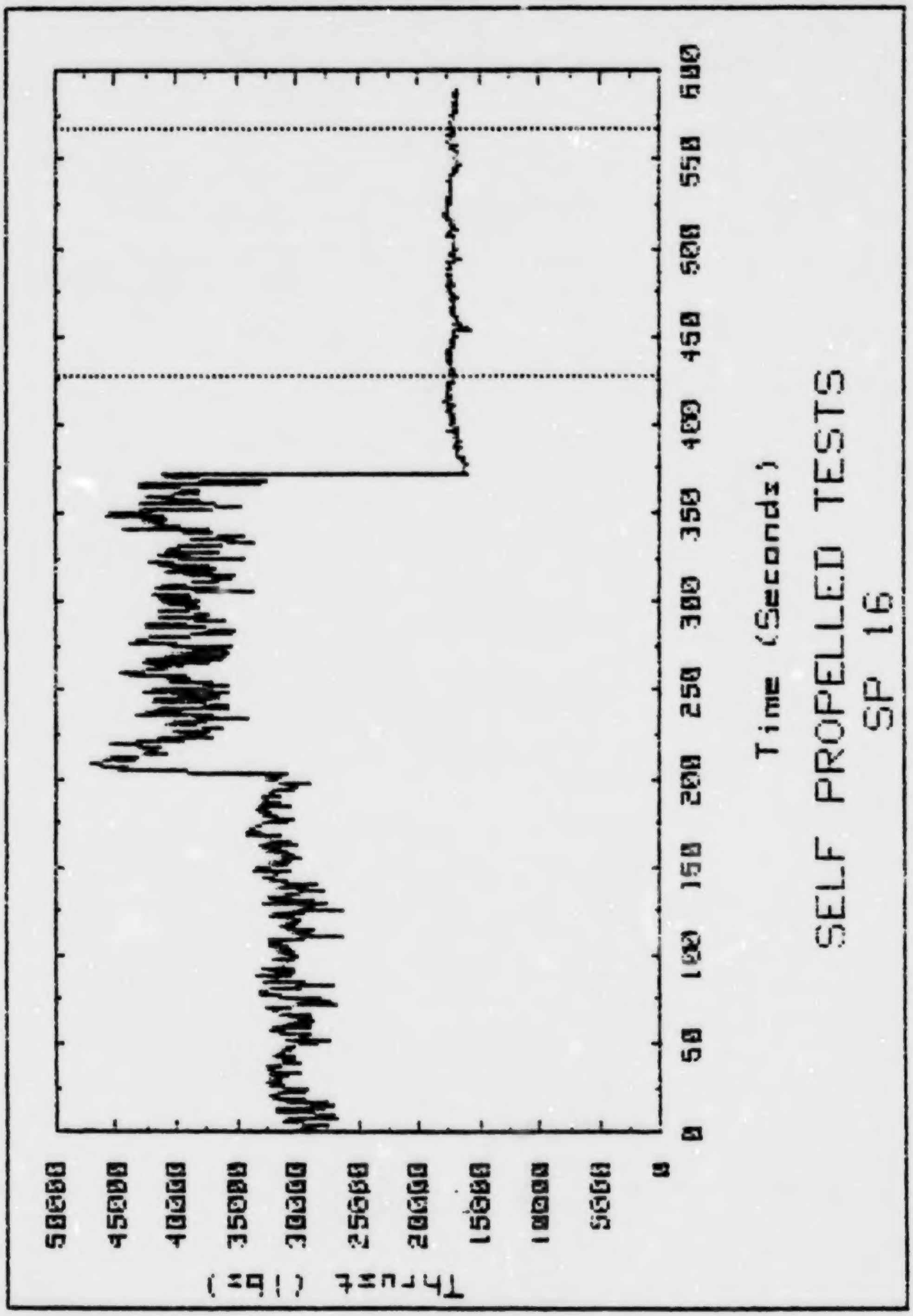


SELF PROPELLED TESTS
SP 16

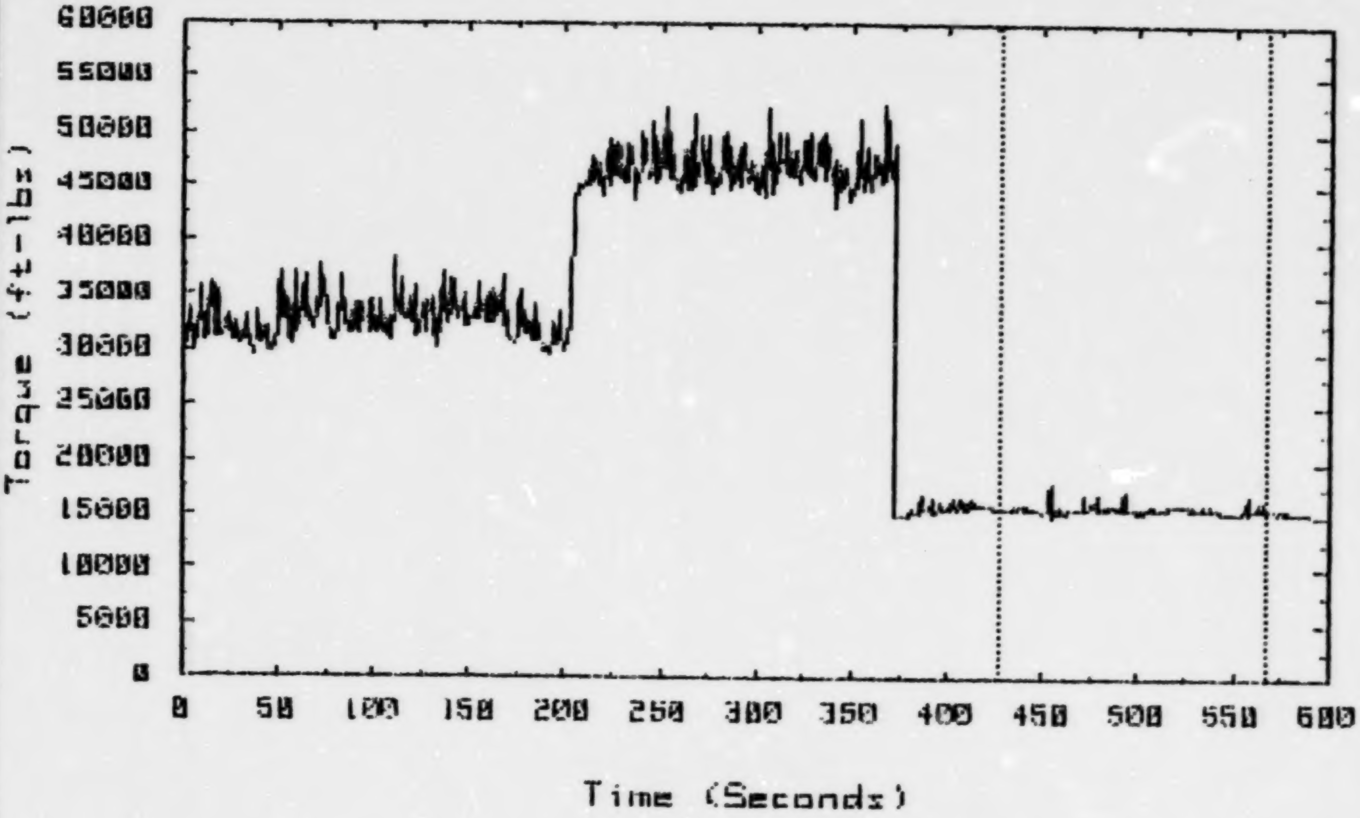


SELF PROPELLED TESTS
SP 16

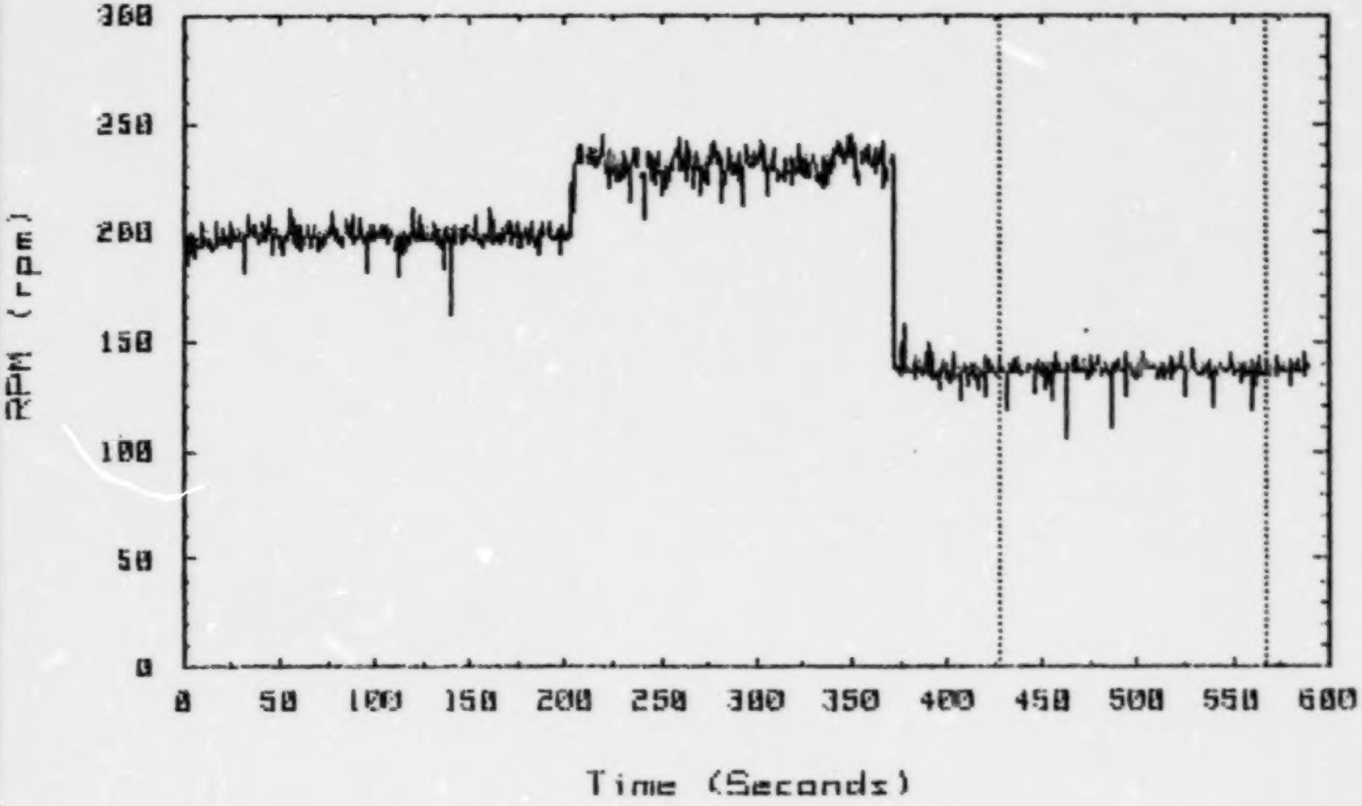
```
               Test Results for Test SP_16C:  02/24/86, 10:42:54
               For the Interval Between  427  sec and  568  sec

     CHANNEL                          MAXIMUM     MINIMUM       MEAN      STDRD DEV

   1  Thrust (lbs)                    17365.0     15783.9     17231.8        290.0
   2  Torque (ft-lbs)                 17773.7     15126.1     15728.4        277.7
   3  RPM (rpm)                         145.9       105.7       137.7          3.0
   4  Ship Speed (kts)                    1.5          .7         1.1           .2
   6  Shaft Horsepower                  468.4       313.2       412.3         11.5


               Test Results for Test SP_16C:  02/24/86, 10:42:54
               For the Interval Between  427  sec and  568  sec

              Average Ship Speed                  1.1    kts
              Average Thrust                  17231.8    lbs
              Average Torque                  15728.4    ft-lbs
              Average RPM                       137.7    RPM
              Average Shaft Horsepower          412.3    HP
              Average Ice Thickness            1.4583    ft
              Mean Advance Coeff., Js          0.0933
              Thrust Coefficient, Kt          3.231E-01
              Torque Coefficient, Kq          3.469E-02

--------------------------------------------------------------------------------

                         RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs         1.555E+04                      2.080E+04
Thrust Deduction             9.737E-02                     -2.069E-01
Propulsive Coeff.            1.249E-01                      1.670E-01

--------------------------------------------------------------------------------

                           Thrust Identity                Torque Identity

Advance Coefficient           -0.1260                       -0.0202
Thrust Coefficient             3.231E-01                     2.904E-01
Torque Coefficient             3.900E-02                     3.469E-02
Advance Velocity,fps          -2.50                         -.39
Effective Wake                 2.372E+00                     1.217E+00
Open Prop Eff.                -1.689E-01                    -2.691E-02
Relative Rotative Eff          1.124E+00                     1.113E+00
Hull Efficiency (Res. Form 1) -6.560E-01                    -4.164E+00
Hull Efficiency (Res. Form 2) -8.799E-01                    -5.563E+00
```



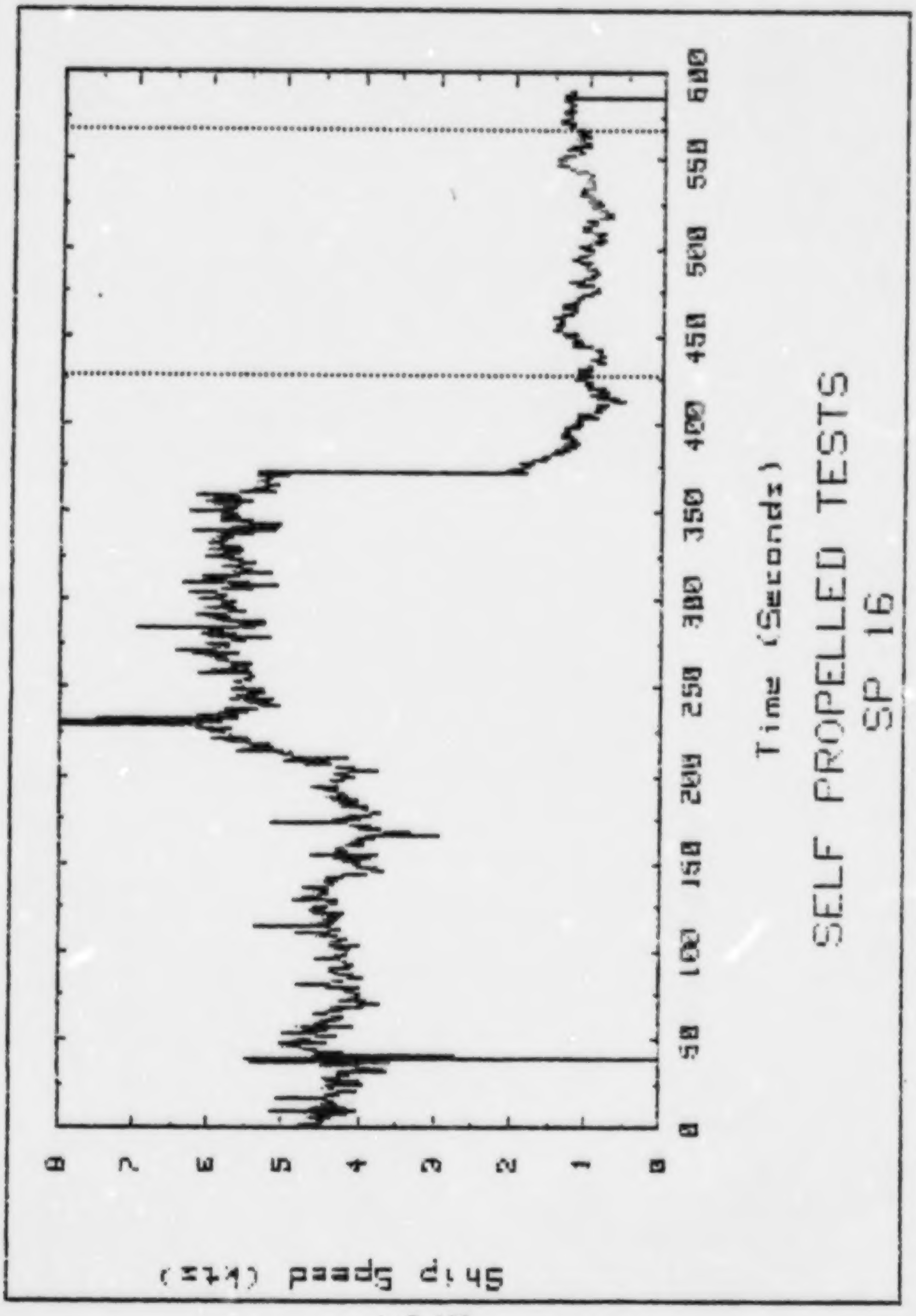
SELF PROPELLED TESTS
SP 16



SELF PROPELLED TESTS
SP 16

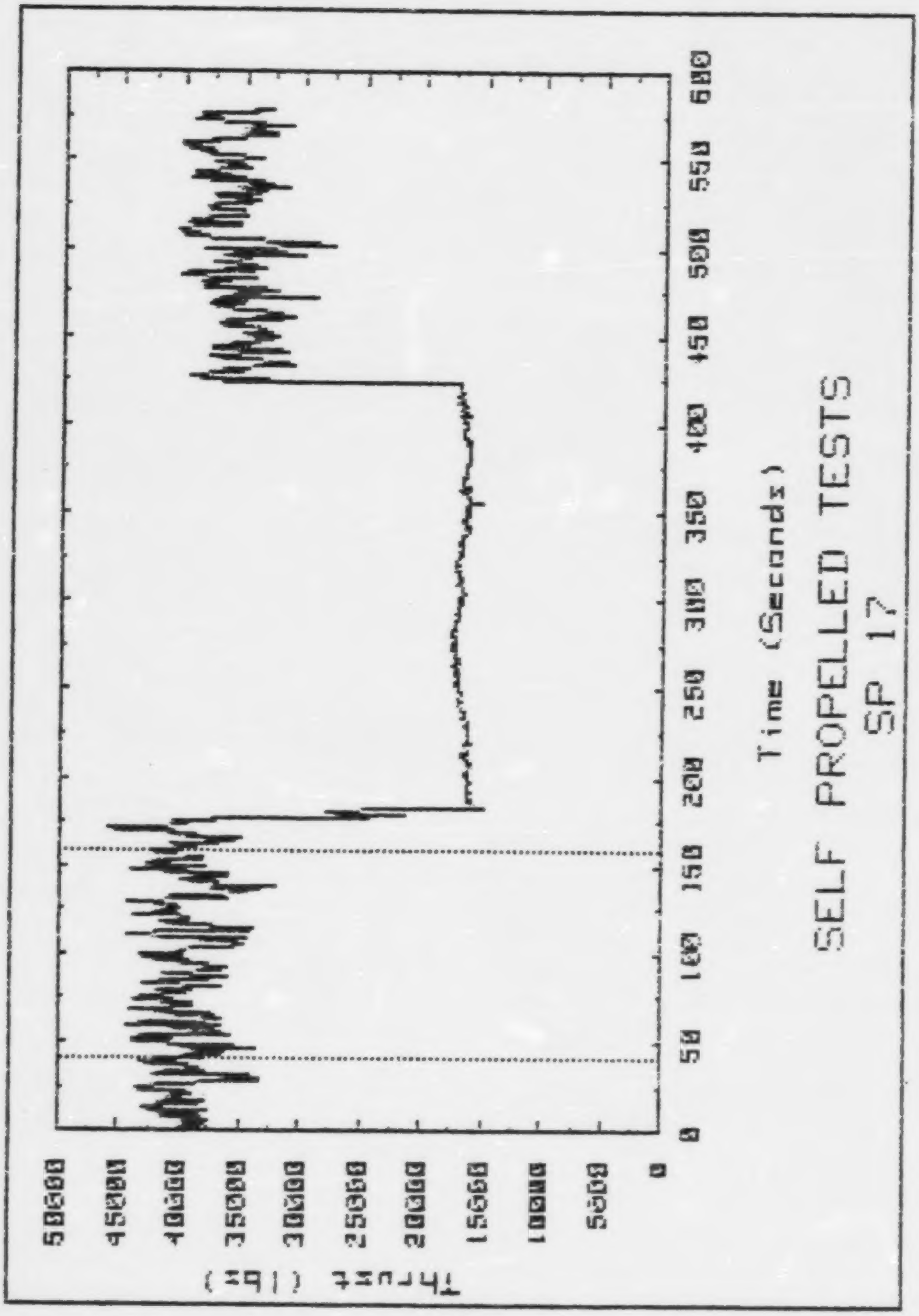


SELF PROPELLED TESTS
SP 16

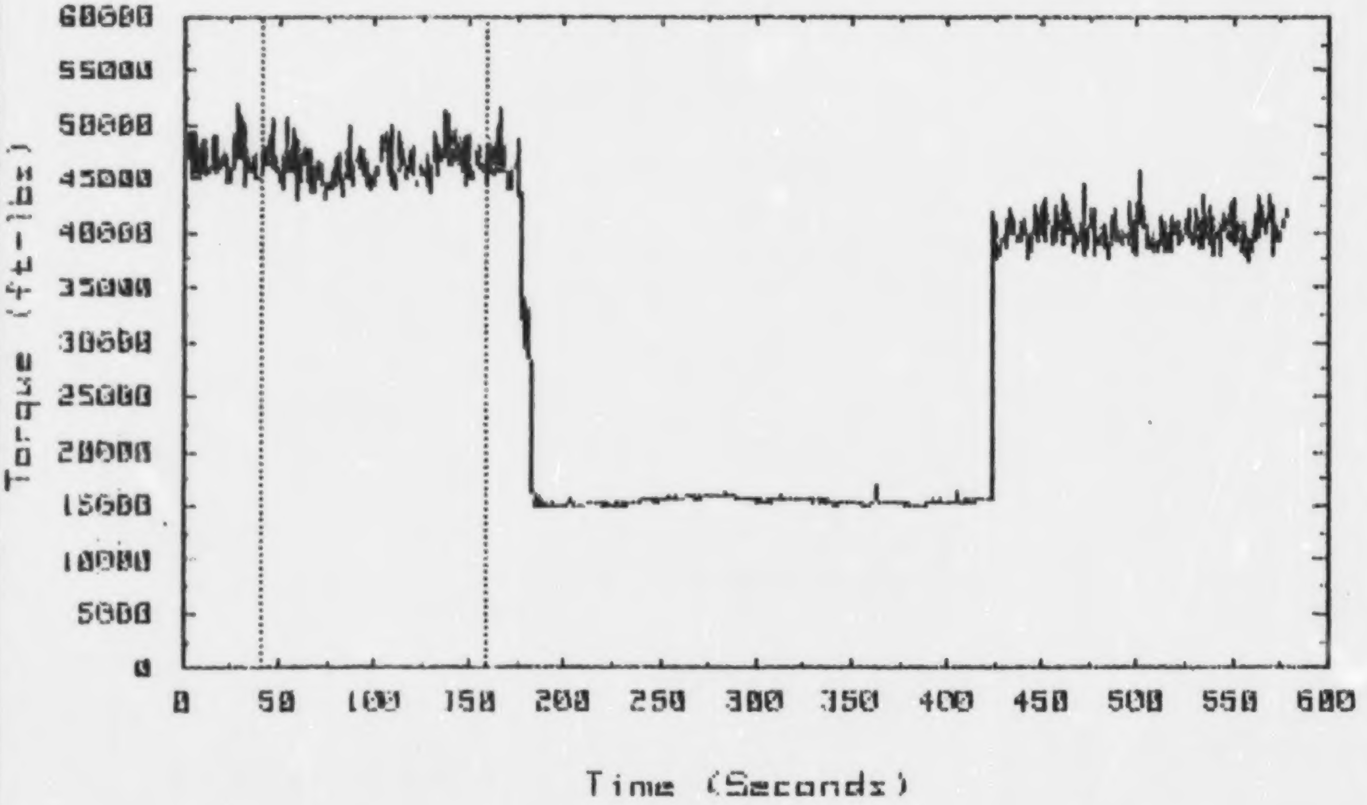


SELF PROPELLED TESTS
SP 16

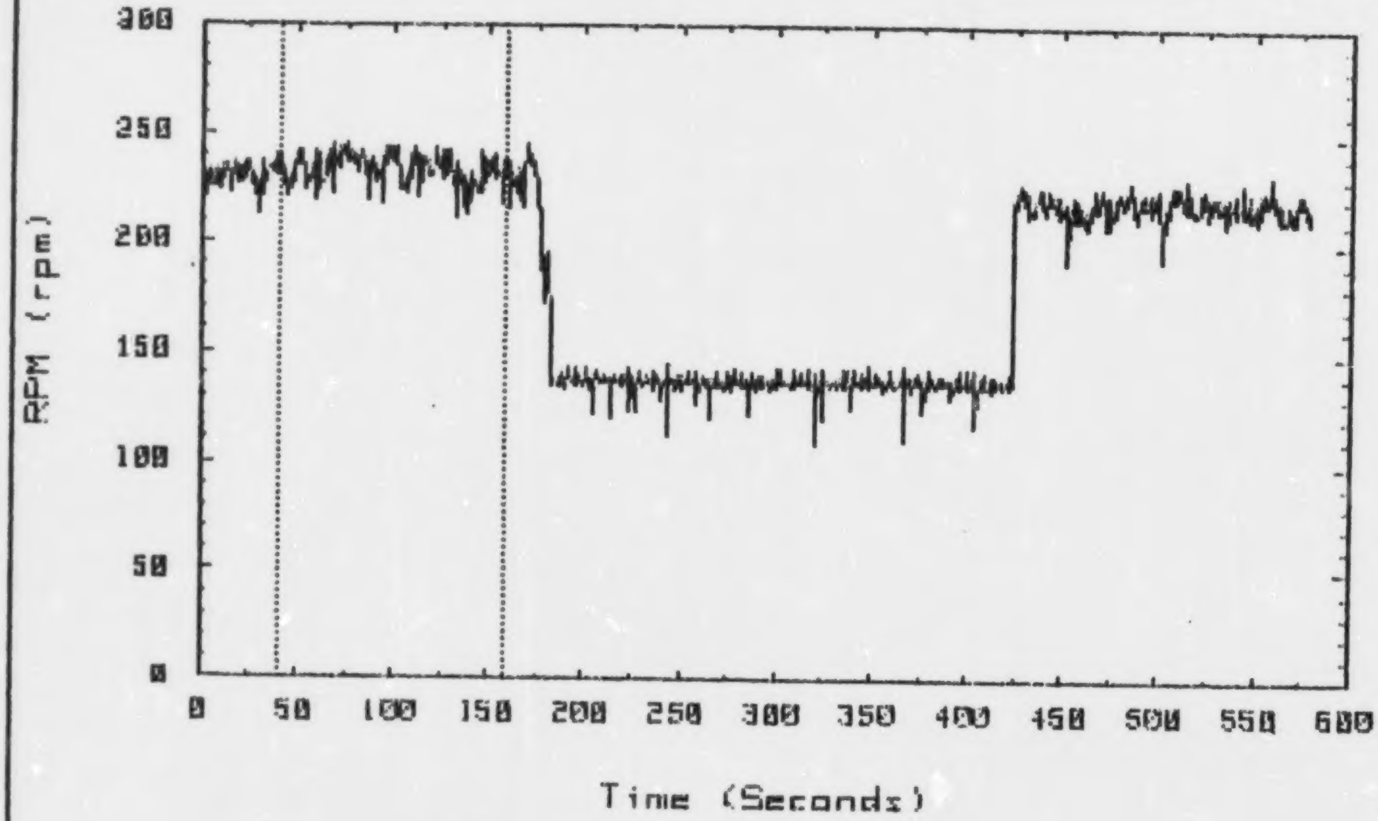
```
              Test Results for Test SP_17A:  02/24/86, 11:04:43
              For the Interval Between  41  sec and  158  sec

  CHANNEL                              MAXIMUM     MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                       44446.2     31317.9     33401.8       2467.2
 2  Torque (ft-lbs)                    51309.6     43233.2     46553.6       1499.3
 3  RPM (rpm)                            244.6       210.2       233.4          5.7
 4  Ship Speed (kts)                       7.2         4.1         6.0           .4
 6  Shaft Horsepower                    2217.5      1055.3      2067.7         44.6


              Test Results for Test SP_17A:  02/24/86, 11:04:43
              For the Interval Between  41  sec and  158  sec

             Average Ship Speed                   6.0   kts
             Average Thrust                   33401.8   lbs
             Average Torque                   46553.3   ft-lbs
             Average RPM                        233.4   RPM
             Average Shaft Horsepower          2067.7   HP
             Average Ice Thickness             1.3333   ft
             Mean Advance Coeff., Js           0.3046
             Thrust Coefficient, Kt            2.571E-01
             Torque Coefficient, Kq            3.574E-02

--------------------------------------------------------------------------------

                         RESISTANCE FORM 1               RESISTANCE FORM 2

Total Resistance,lbs         3.449E+04                       3.021E+04
Thrust Deduction             1.246E-01                       2.332E-01
Propulsive Coeff.            3.053E-01                       2.674E-01

--------------------------------------------------------------------------------

                          Thrust Identity                 Torque Identity

Advance Coefficient          0.3839                         -0.0499
Thrust Coefficient           2.571E-01                       2.995E-01
Torque Coefficient           3.099E-02                       3.574E-02
Advance Velocity,fps         2.77                           -1.65
Effective Wake               7.246E-01                       1.134E+00
Open Prop Eff.               1.107E-01                      -6.302E-02
Relative Rotative Eff        6.873E-01                       3.582E-01
Hull Efficiency (Res. Form 1)  3.179E+00                    -5.352E+00
Hull Efficiency (Res. Form 2)  2.785E+00                    -4.687E+00
```



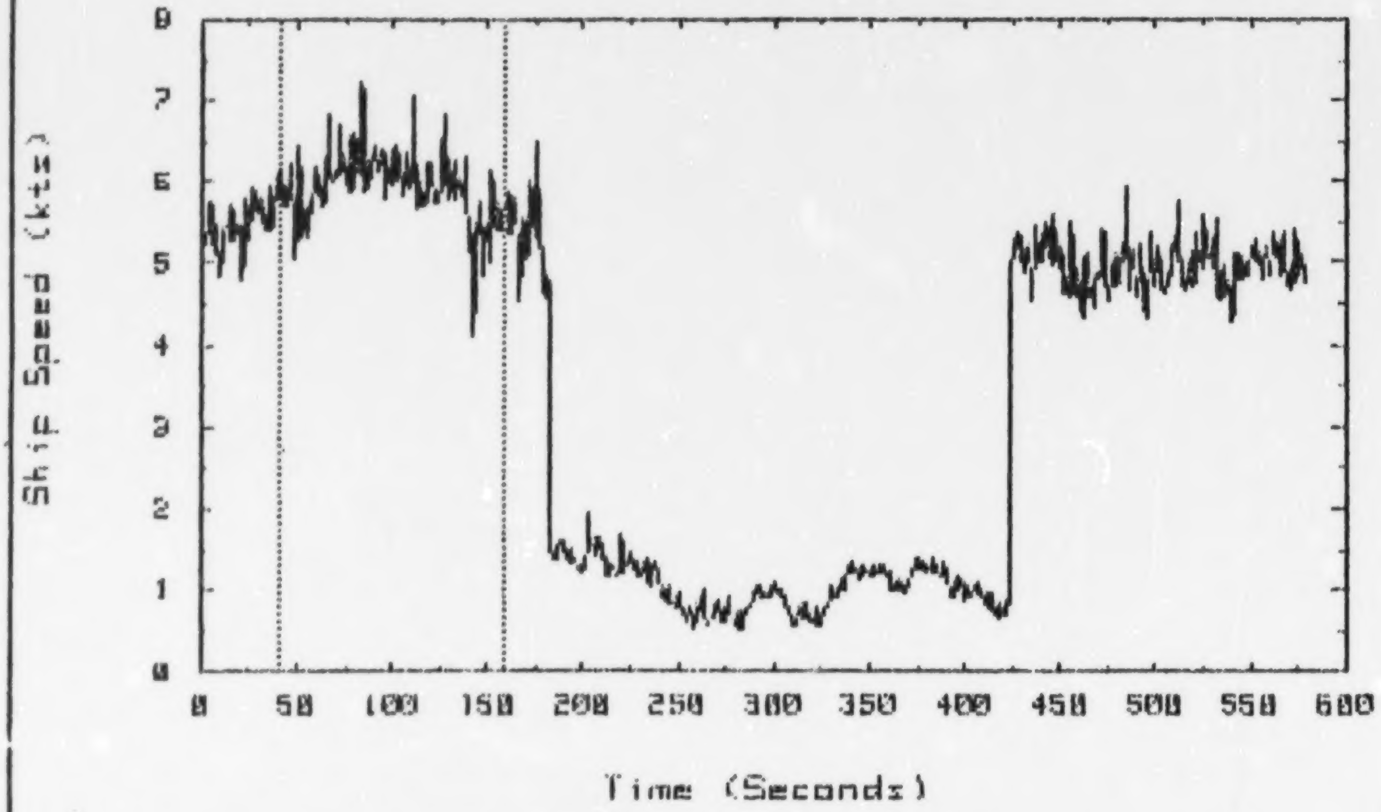
SELF PROPELLED TESTS
SP 17



SELF PROPELLED TESTS
SP 17

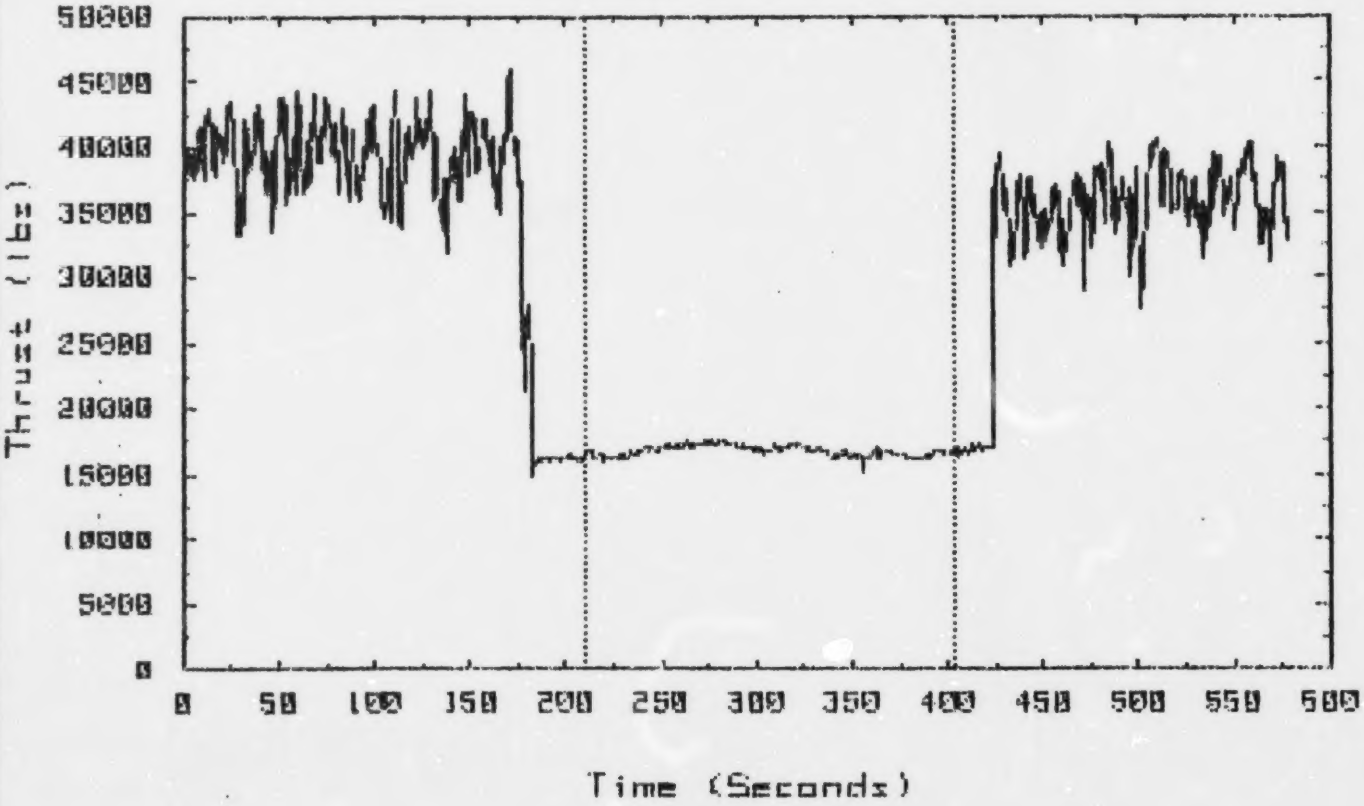


SELF PROPELLED TESTS
SP 17

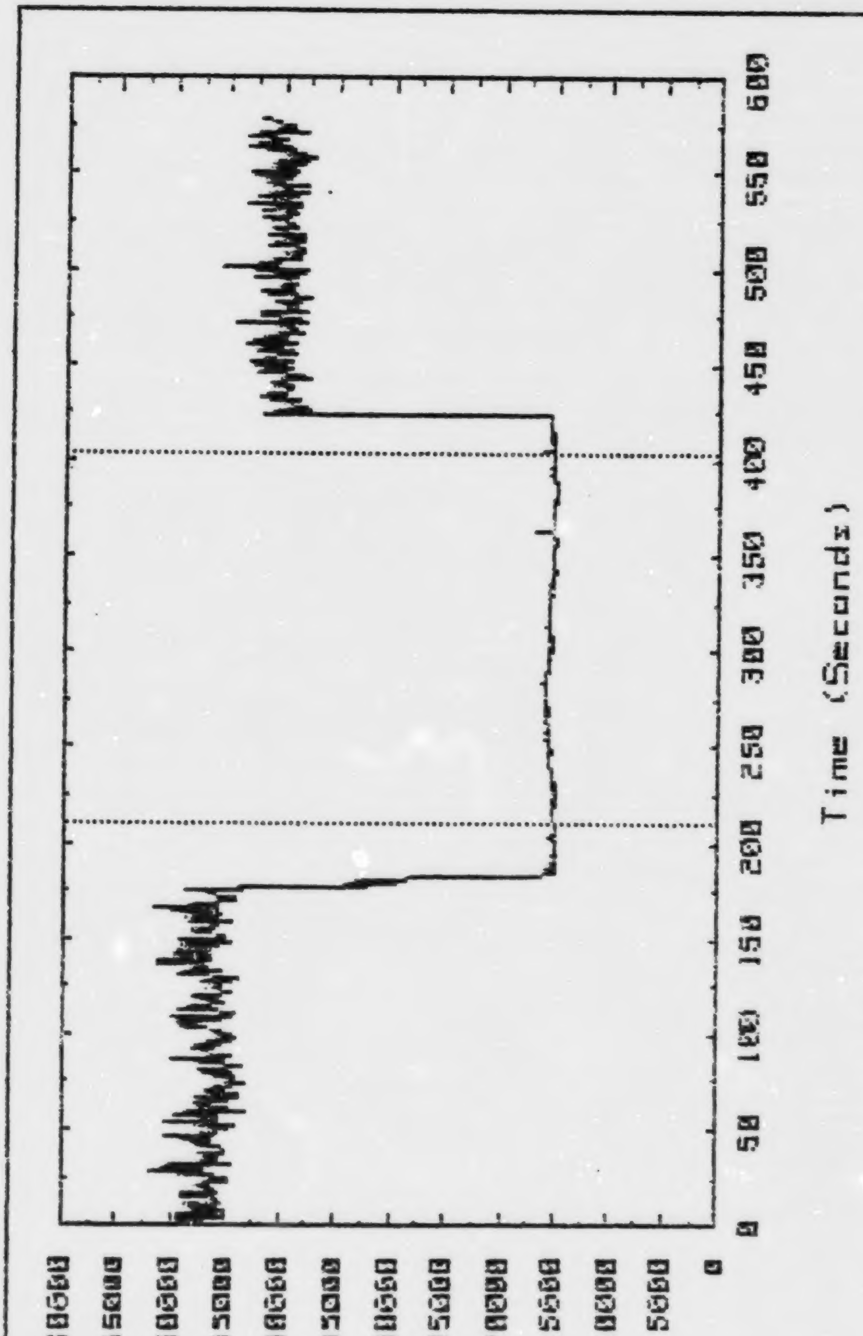


SELF PROPELLED TESTS
SP 17

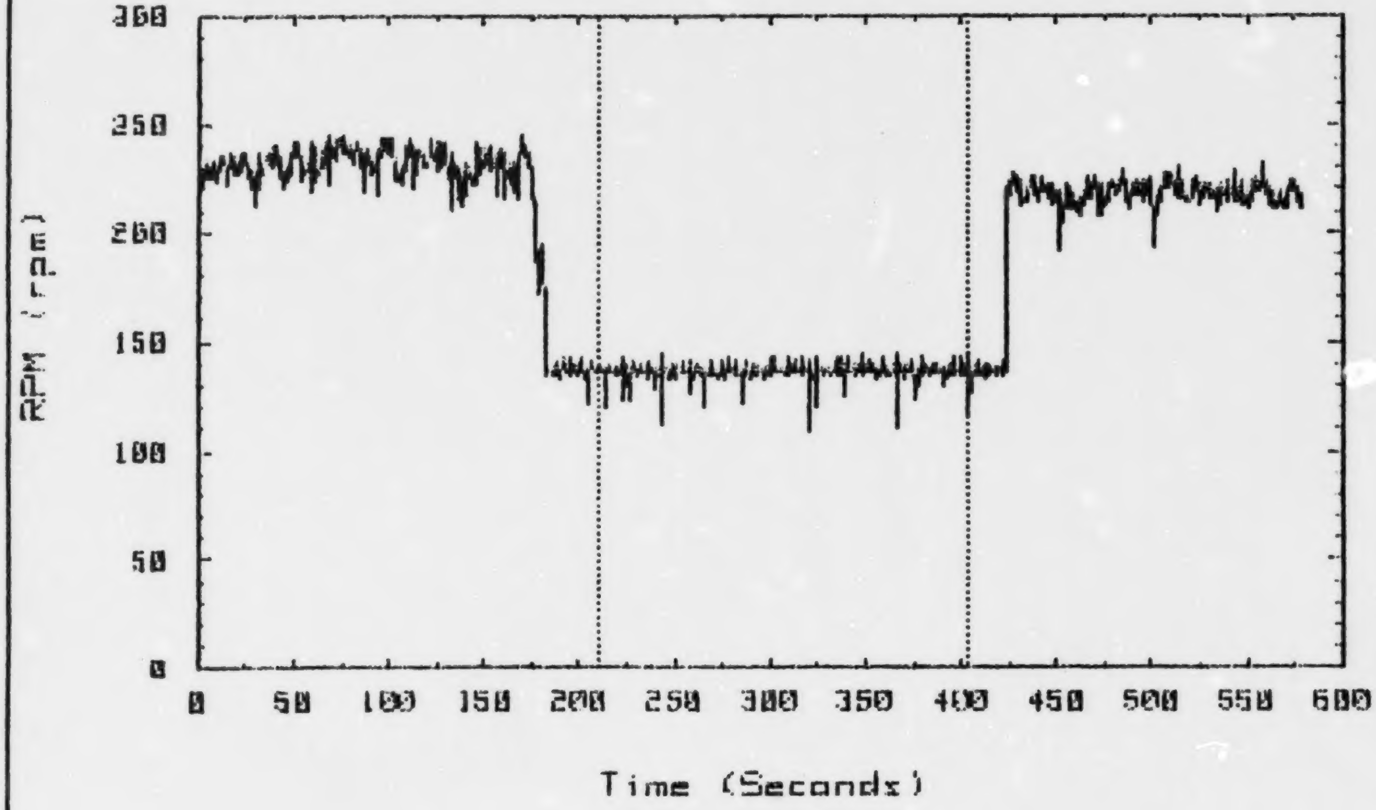
```
            Test Results for Test SP_178:  02/24/86, 11:04:43
            For the Interval Between  211  sec and  403  sec

   CHANNEL                            MAXIMUM      MINIMUM       MEAN      STDRD DEV

 1  Thrust (lbs)                      17675.8      15169.0      16812.3       391.9
 2  Torque (ft-lbs)                   16784.2      14992.4      15492.6       263.5
 3  RPM (rpm)                           144.8        109.5        137.1         2.8
 4  Ship Speed (kts)                      1.7           .5          1.0          .2
 6  Shaft Horsepower                    436.9        325.2        404.3        10.5


            Test Results for Test SP_178:  02/24/86, 11:04:43
            For the Interval Between  211  sec and  403  sec

          Average Ship Speed                1.0    kts
          Average Thrust                16812.3    lbs
          Average Torque                15492.6    ft-lbs
          Average RPM                     137.1    RPM
          Average Shaft Horsepower        404.3    HP
          Average Ice Thickness          1.0417    ft
          Mean Advance Coeff., Js        0.0880
          Thrust Coefficient, Kt         3.182E-01
          Torque Coefficient, Kq         3.449E-02

-----------------------------------------------------------------------------

                        RESISTANCE FORM 1              RESISTANCE FORM 2

Total Resistance,lbs       8.993E+03                      1.114E+04
Thrust Deduction           4.651E-01                      3.373E-01
Propulsive Coeff.          6.914E-02                      8.566E-02

-----------------------------------------------------------------------------

                          Thrust Identity               Torque Identity

Advance Coefficient         -0.1114                      -0.0144
Thrust Coefficient           3.182E-01                    2.386E-01
Torque Coefficient           3.831E-02                    3.449E-02
Advance Velocity,fps        -2.16                        -.29
Effective Wake               2.265E+00                    1.164E+00
Open Prop Eff.              -1.473E-01                   -1.920E-02
Relative Rotative Eff        1.111E+00                    1.102E+00
Hull Efficiency (Res. Form 1) -4.226E-01                 -3.262E+00
Hull Efficiency (Res. Form 2) -5.238E-01                 -4.041E+00
```



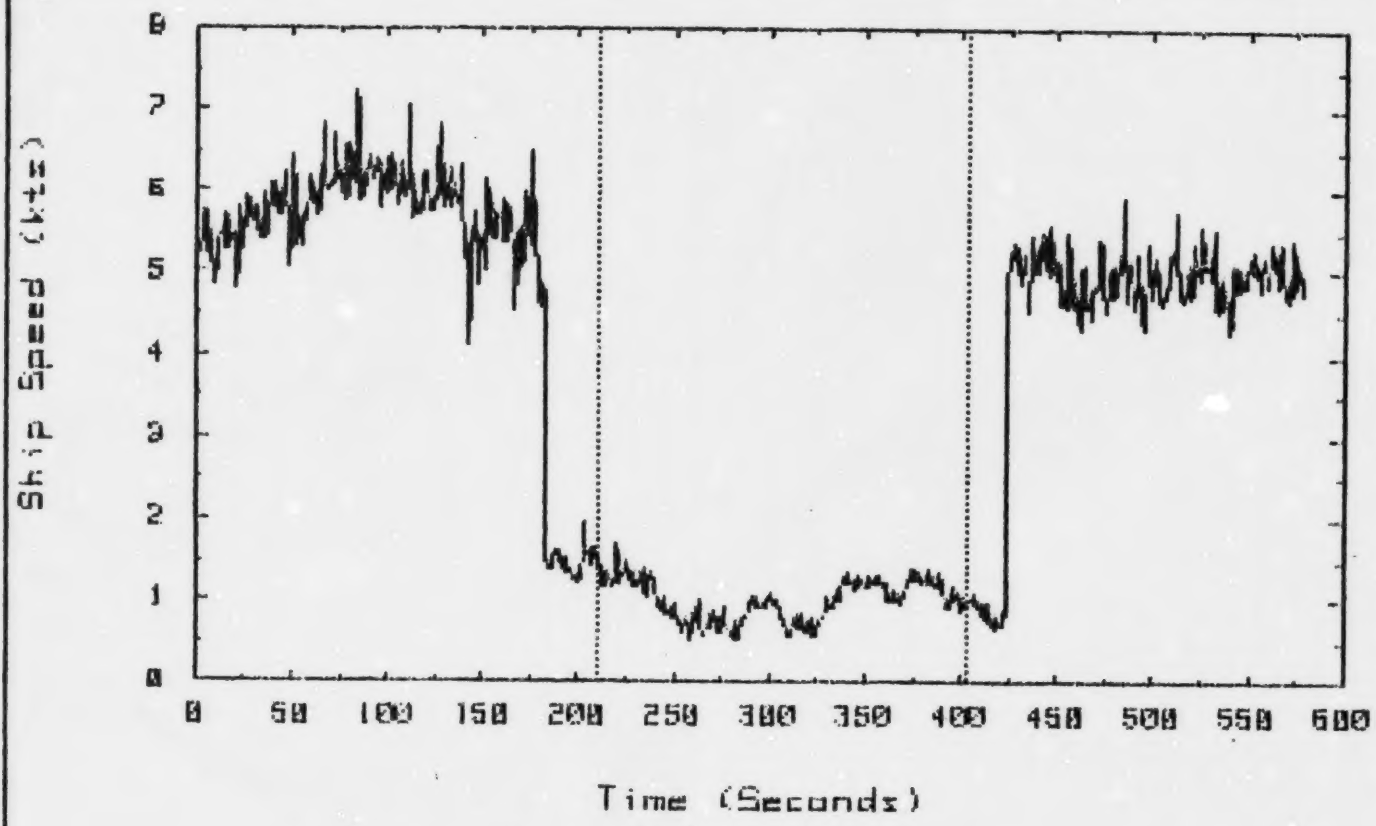
SELF PROPELLED TESTS
SP 17



SELF PROPELLED TESTS
SP 17

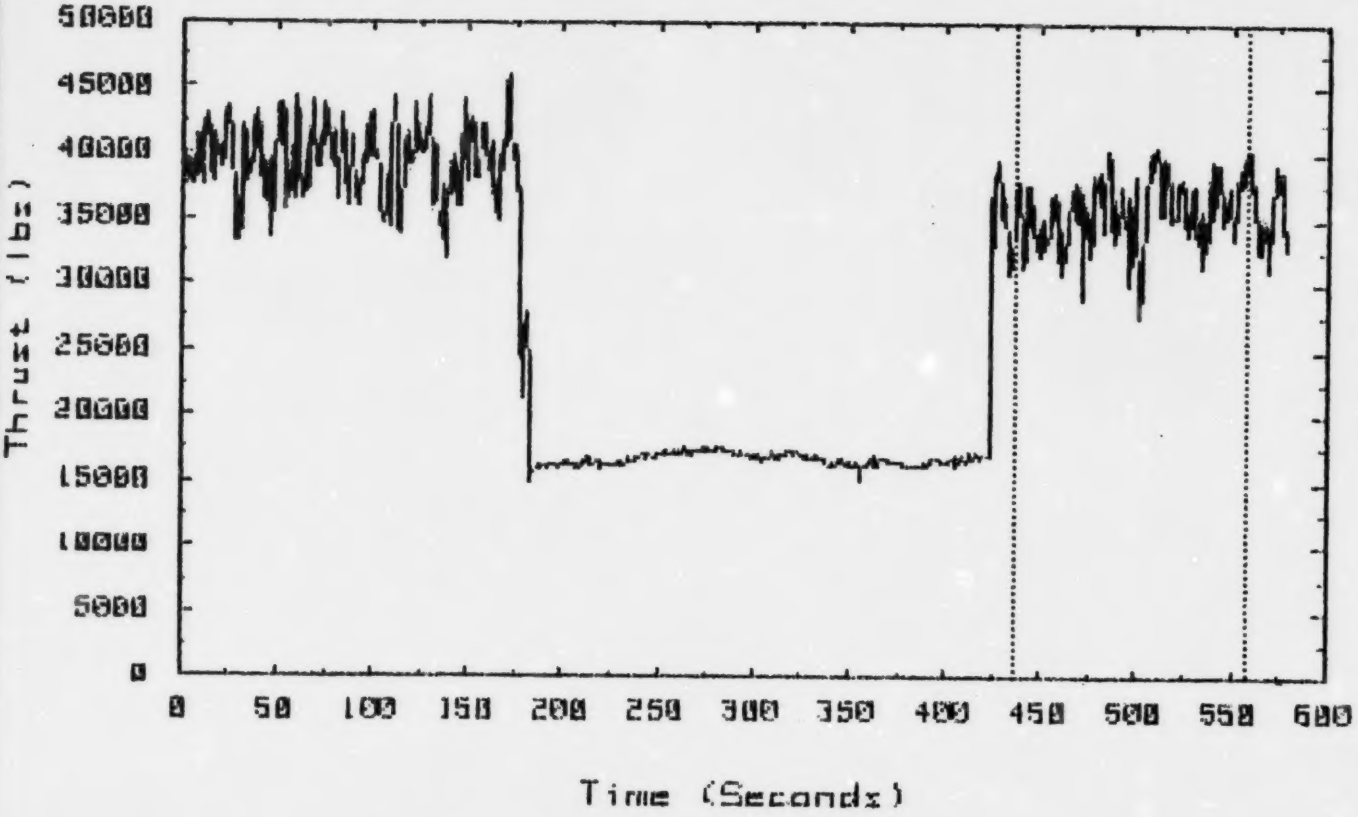


SELF PROPELLED TESTS
SP 17

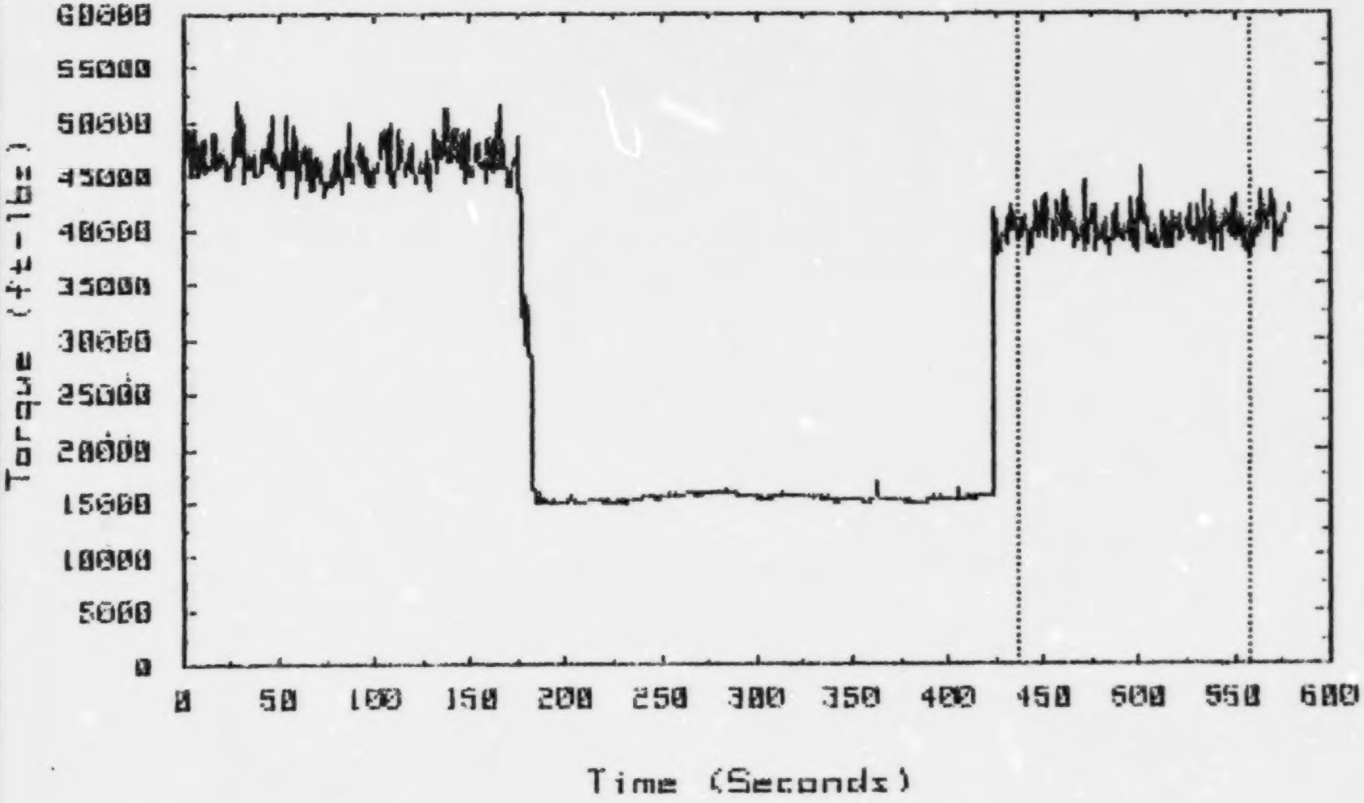


SELF PROPELLED TESTS
SP 17

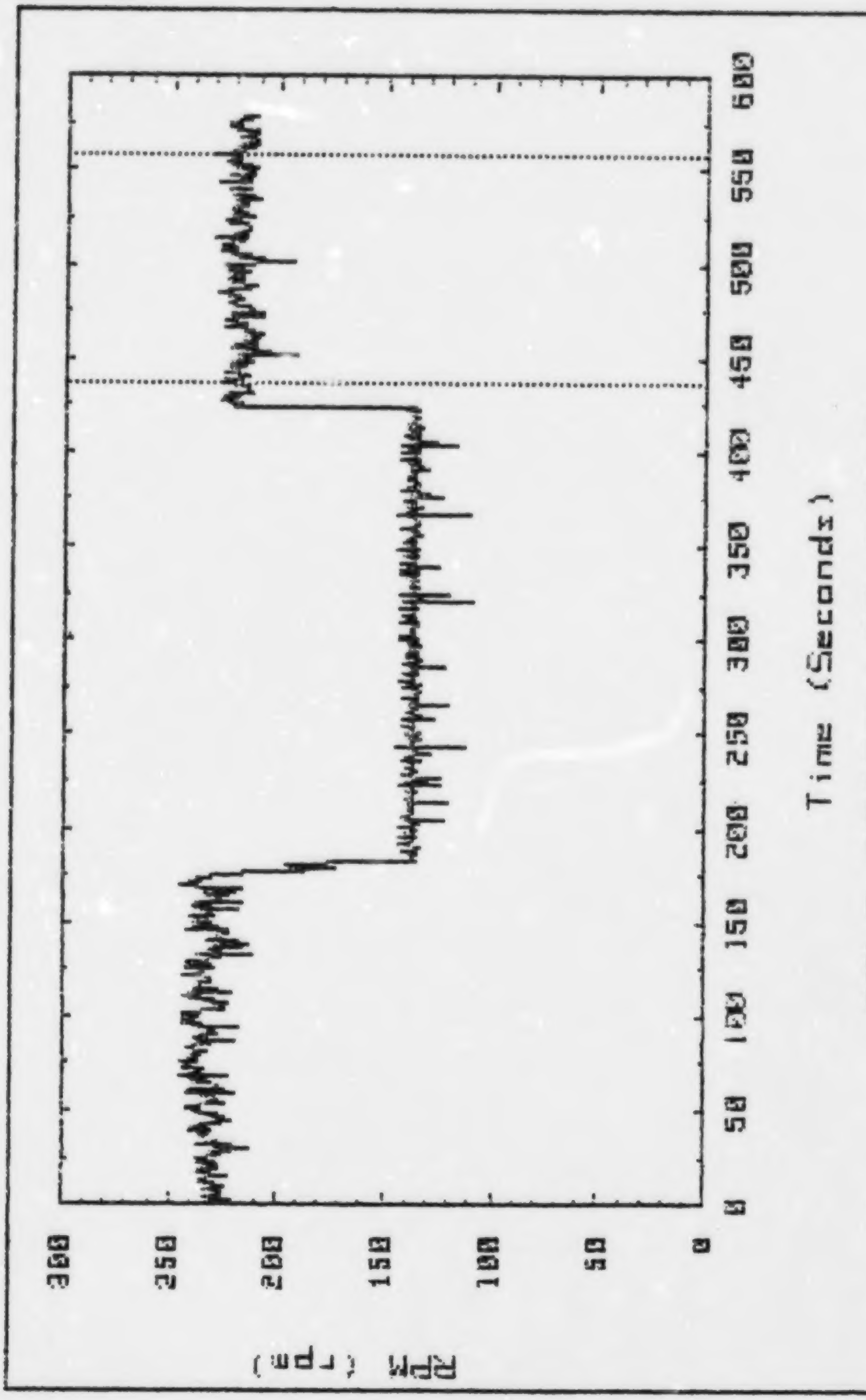
```
              Test Results for Test SP_17C:  02/24/86, 11:04:43
              For the Interval Between  436  sec and  558  sec

  CHANNEL                          MAXIMUM     MINIMUM      MEAN      STDRD DEV

1  Thrust (lbs)                    40473.2     27466.4    35776.5      2254.9
2  Torque (ft-lbs)                 45747.0     37510.2    40296.0      1226.4
3  RPM (rpm)                         230.2       191.1      218.6         4.6
4  Ship Speed (kts)                    5.9         4.3        5.0          .3
6  Shaft Horsepower                 1913.0      1457.4     1677.0        42.7


              Test Results for Test SP_17C:  02/24/86, 11:04:43
              For the Interval Between  436  sec and  558  sec

             Average Ship Speed                   5.0    kts
             Average Thrust                   35776.5    lbs
             Average Torque                   40296.0    ft-lbs
             Average RPM                        218.6    RPM
             Average Shaft Horsepower          1677.0    HP
             Average Ice Thickness             1.2500    ft
             Mean Advance Coeff., Js           0.2706
             Thrust Coefficient, Kt            2.660E-01
             Torque Coefficient, Kq            3.525E-02

-----------------------------------------------------------------------------------

                               RESISTANCE FORM 1                RESISTANCE FORM 2

Total Resistance,lbs              2.775E+04                        2.475E+04
Thrust Deduction                  2.235E-01                        3.081E-01
Propulsive Coeff.                 2.524E-01                        2.249E-01

-----------------------------------------------------------------------------------

                                Thrust Identity                   Torque Identity

Advance Coefficient               0.0565                          -0.0361
Thrust Coefficient                2.660E-01                        2.953E-01
Torque Coefficient                3.195E-02                        3.525E-02
Advance Velocity,fps              1.75                            -1.12
Effective Wake                    7.913E-01                        1.133E+00
Open Prop Eff.                    7.482E-02                       -4.795E-02
Relative Rotative Eff             9.066E-01                        9.003E-01
Hull Efficiency (Res. Form 1)     3.720E+00                       -5.325E+00
Hull Efficiency (Res. Form 2)     3.315E+00                       -5.191E+00
```



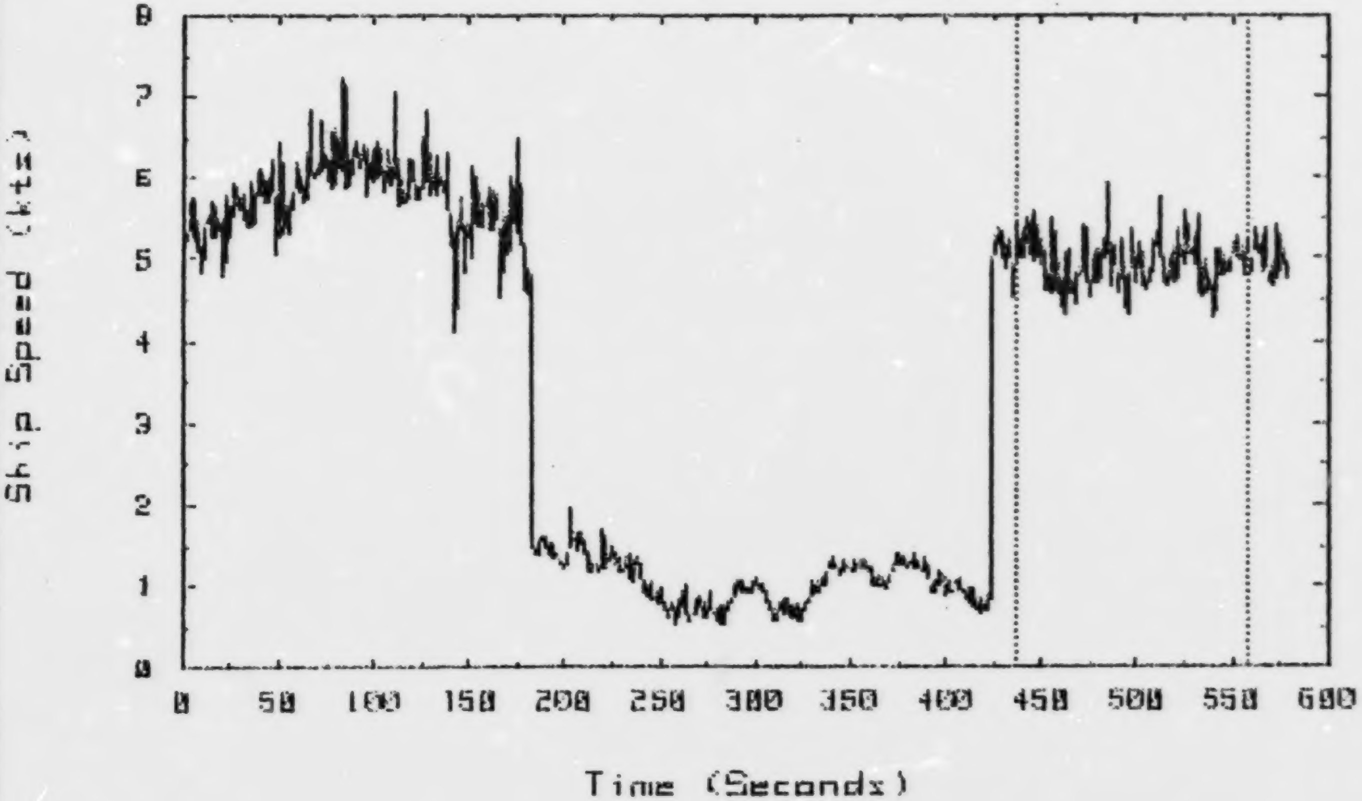
SELF PROPELLED TESTS
SP 17



SELF PROPELLED TESTS
SP 17



SELF PROPELLED TESTS
SP 17



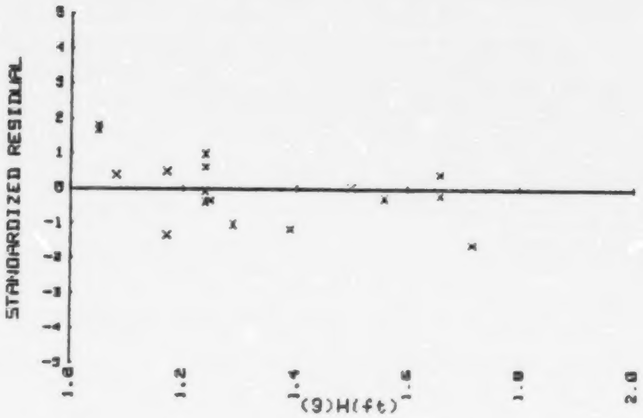
SELF PROPELLED TESTS
SP 17

APPENDIX E

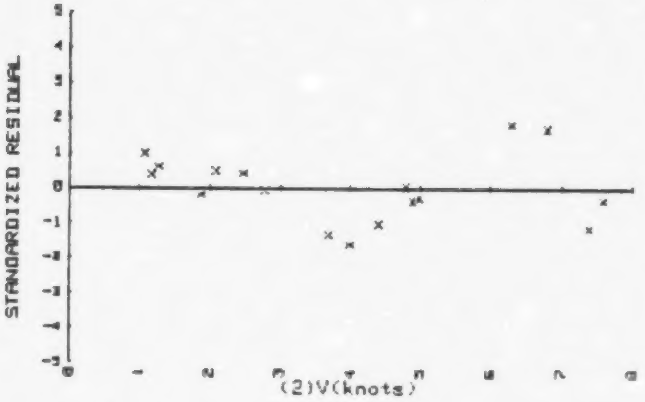
REGRESSIONS FOR LEVEL ICE RESISTANCE EQUATIONS

```
The data and related information are stored in GOODTOW:HP9121,704,1


                    1252C TOWED RESISTANCE TESTS OF 140' WTGB


Data file name: DATA

Number of observations: 17
Number of variables: 22

Variables names:
   1. TEST ID
   2. V(knots)
   3. H(in)
   4. 24FDH(Chr)
   5. RTOT(lbs)
   6. ROW(lbs)
   7. Rice(lbs)
   8. V(fps)
   9. H(ft)
  10. SIG(psi)
  11. SIG(psf)
  12. R*
  13. V*
  14. V**
  15. V***
  16. V****
  17. V*****
  18. SIG*
  19. SIG**
  20. L/H
  21. B/H
  22. V******

Subfiles:  NONE
```

1252C TOWED RESISTANCE TESTS OF 140' WTGB



1252C TOWED RESISTANCE TESTS OF 140' WTGB



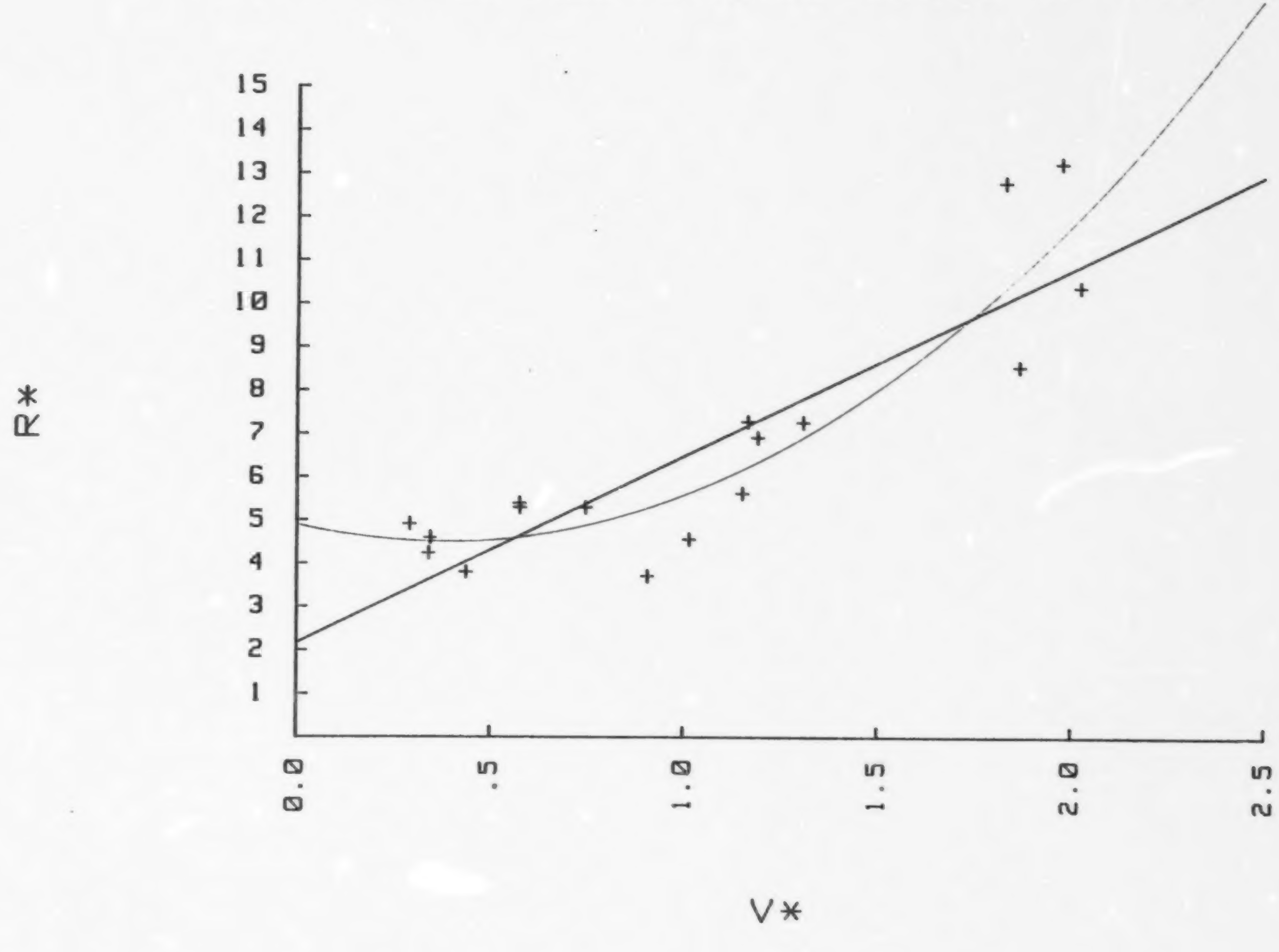
```
********************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                   1252C TOWED RESISTANCE TESTS OF 140' WTGB
********************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (13)V*



                                                     STANDARD      COEFF. OF
VARIABLE      N             MEAN         VARIANCE      DEVIATION      VARIATION
V*            17         1.04549           .35579         .59649       57.05321
R*            17         6.67658          8.77822        2.96281       44.37609

CORRELATION =    .87103
```

```
SELECTED DEGREE OF REGRESSION =  2
R-SQUARED =  .83409
STANDARD ERROR OF ESTIMATE = 1.29012496303


                            ANALYSIS OF VARIANCE TABLE


SOURCE             DF        SUM OF SQUARES           MEAN SQUARE        F-VALUE

TOTAL              16             140.45147
REGRESSION          2             117.14956              58.57478          35.19
X^1                 1             106.55860             106.55860          64.02
X^2                 1              10.59096              10.59096           6.36
RESIDUAL           14              23.30191               1.66442


                  REGRESSION COEFFICIENTS         STANDARD ERROR
VARIABLE         STD. FORMAT           E-FORMAT     REG. COEFFICIENT     T-VALUE

'CONSTANT'           4.89237  .489236530744E+01              1.26355        3.87
 X^1                -2.08744 -.208744477991E+01              2.59952        -.80
 X^2                 2.77791  .277791169033E+01              1.10124        2.52


                                    95 % CONFIDENCE INTERVAL
                  COEFFICIENT         LOWER LIMIT        UPPER LIMIT

'CONSTANT'            4.89237            2.18165            7.60308
 X^1                 -2.08744           -7.66426            3.48937
 X^2                  2.77791             .41539            5.14043
```

```
SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .75869
STANDARD ERROR OF ESTIMATE = 1.50317161127


                            ANALYSIS OF VARIANCE TABLE


SOURCE             DF        SUM OF SQUARES           MEAN SQUARE         F-VALUE

TOTAL              16            140.45147
REGRESSION          1            106.55860             106.55860           47.16
X^1                 1            106.55860             106.55860           47.16
RESIDUAL           15           .  33.89287               2.25952


                  REGRESSION COEFFICIENTS         STANDARD ERROR
VARIABLE         STD. FORMAT           E-FORMAT     REG. COEFFICIENT      T-VALUE

'CONSTANT'           2.15329  .215329325501E+01                .75284         2.86
 X^1                 4.32648  .432647940300E+01                .63001         6.87


                                    95 % CONFIDENCE INTERVAL
                  COEFFICIENT        LOWER LIMIT         UPPER LIMIT

'CONSTANT'            2.15329             .54826            3.75832
 X^1                  4.32648            2.98331            5.66965
```

```
                              TABLE OF RESIDUALS

                                                              STANDARDIZED
OBS#     OBSERVED Y      PREDICTED Y          RESIDUAL       RESIDUAL     SIGNIF.
   1        3.69338          6.08637          -2.39299       -1.59196
   2        6.88864          7.31336           -.42472        -.28255
   3        5.27279          4.65433            .61846         .41144
   4        3.77670          4.05408           -.27738        -.18453
   5        7.25477          7.20236            .05241         .03487
   6        4.54412          6.55072          -2.00659       -1.33491
   7        5.27523          5.39050           -.11527        -.07669
   8       12.78833         10.07395           2.71437        1.80576
   9       13.23067         10.70258           2.52809        1.68184
  10        4.88409          3.42505           1.45903         .97064
  11        4.57051          3.65628            .91422         .60820
  12        7.24097          7.81841           -.57744        -.38415
  13        4.21372          3.63860            .57512         .38261
  14       10.37184         10.91067           -.53883        -.35846
  15        5.36844          4.64913            .71932         .47853
  16        8.52555         10.23456          -1.70901       -1.13694
  17        5.60212          7.14091          -1.53879       -1.02370

Durbin-Watson Statistic: 1.04666573735
```

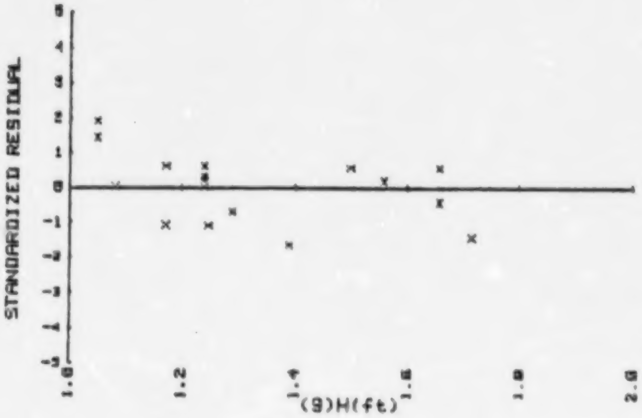
1252C TOWED RESISTANCE TESTS OF 140′ WTGB



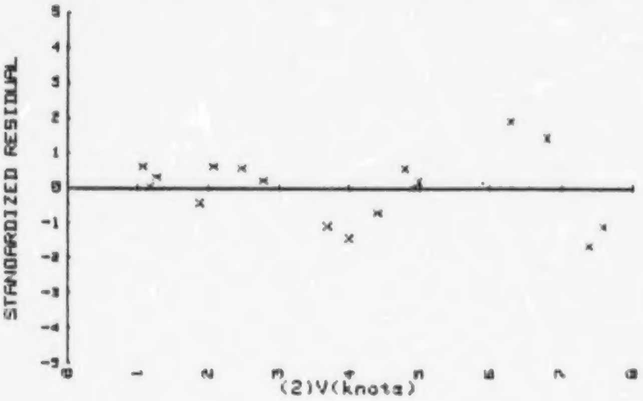
```
******************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                  1252C TOWED RESISTANCE TESTS OF 140' WTGB
******************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (16)V****



                                                     STANDARD      COEFF. OF
VARIABLE       N            MEAN          VARIANCE       DEVIATION      VARIATION
V****         17         1.42791           1.98253         1.40802       98.60703
R*            17         6.67658           8.77822         2.96281       44.37609

CORRELATION =    .90909


SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .82645
STANDARD ERROR OF ESTIMATE = 1.27475964241


                            ANALYSIS OF VARIANCE TABLE


SOURCE             DF          SUM OF SQUARES           MEAN SQUARE        F-VALUE

TOTAL              16              140.45147
REGRESSION          1              116.07629             116.07629          71.43
X^1                 1              116.07629             116.07629          71.43
RESIDUAL           15               24.37518               1.62501


                 REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE         STD. FORMAT           E-FORMAT    REG. COEFFICIENT       T-VALUE

'CONSTANT'           3.94506  .394506406345E+01              .44726          8.82
 X^1                 1.91294  .191294325716E+01              .22634          8.45


                                   95 % CONFIDENCE INTERVAL
                 COEFFICIENT          LOWER LIMIT         UPPER LIMIT

'CONSTANT'           3.94506              2.99151             4.89862
 X^1                 1.91294              1.43039             2.39549
```

```
                    TABLE OF RESIDUALS


                                                      STANDARDIZED
OBS#    OBSERVED Y    PREDICTED Y        RESIDUAL       RESIDUAL       SIGNIF.
   1       3.69338        5.52594        -1.83256       -1.43757
   2       6.88864        6.66616          .22248         .17453
   3       5.27279        4.58432          .68847         .54008
   4       3.77670        4.31430         -.53759        -.42172
   5       7.25477        6.55035          .70442         .55259
   6       4.54412        5.92126        -1.37713       -1.08031
   7       5.27523        5.01603          .25920         .20333
   8      12.78833       10.35651         2.43182        1.90767
   9      13.23067       11.41458         1.81609        1.42465
  10       4.88409        4.11035          .77374         .60697
  11       4.57051        4.17592          .39459         .30954
  12       7.24097        7.22489          .01608         .01261
  13       4.21372        4.17052          .04320         .03389
  14      10.37184       11.78263        -1.41078       -1.10671
  15       5.36844        4.58166          .78678         .61720
  16       8.52555       10.61915        -2.09360       -1.64235
  17       5.60212        6.48732         -.88520        -.69441

Durbin-Watson Statistic: 1.54544648777
```

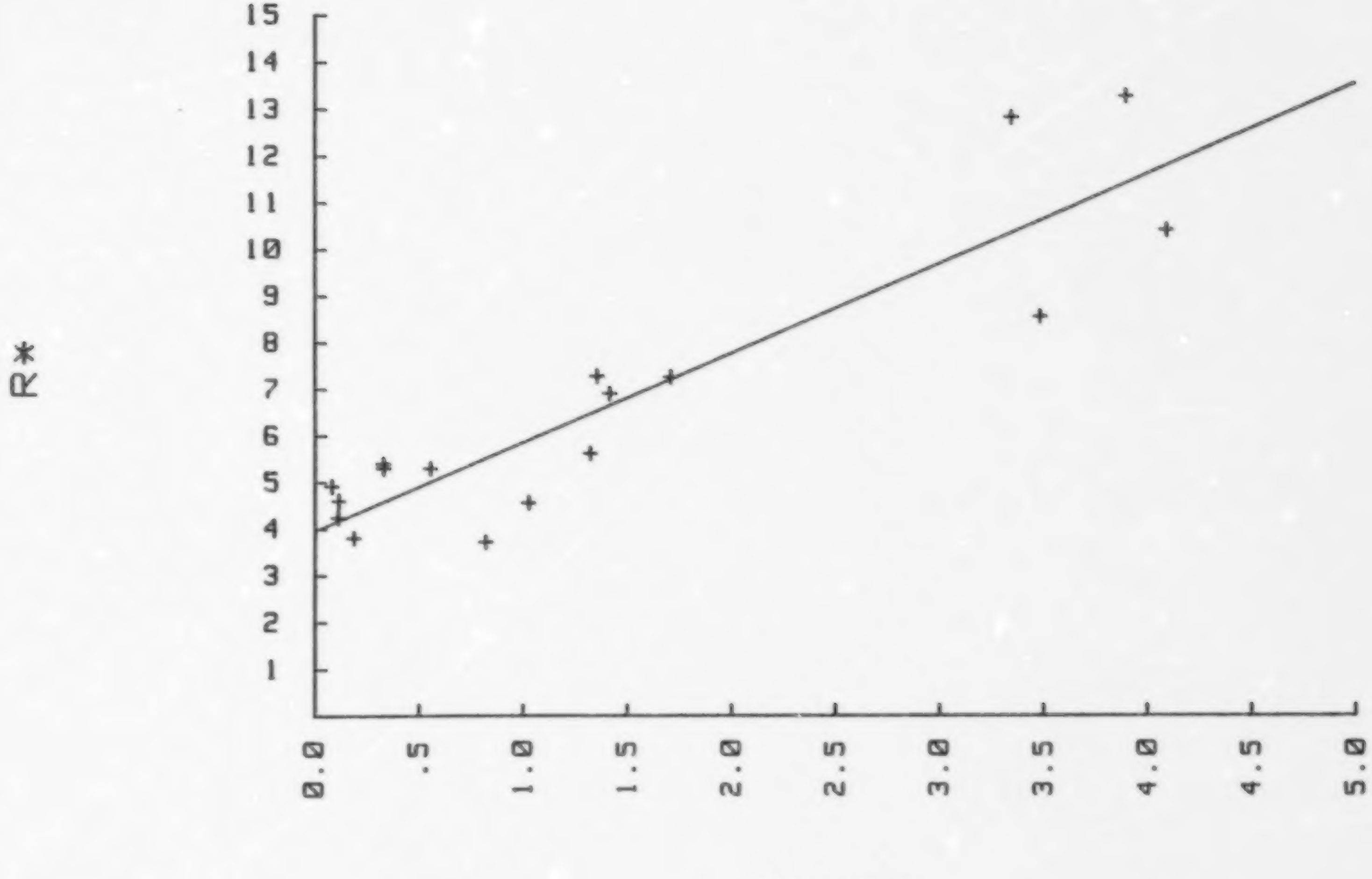
1252C TOWED RESISTANCE TESTS OF 140' WTGB



1252C TOWED RESISTANCE TESTS OF 140' WTGB

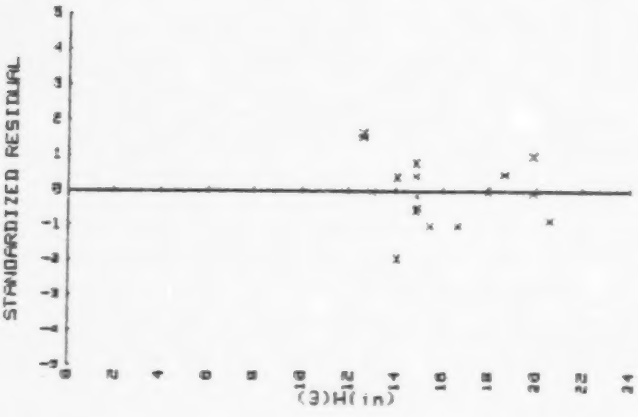


1252C TOWED RESISTANCE TESTS OF 140′ WTGB

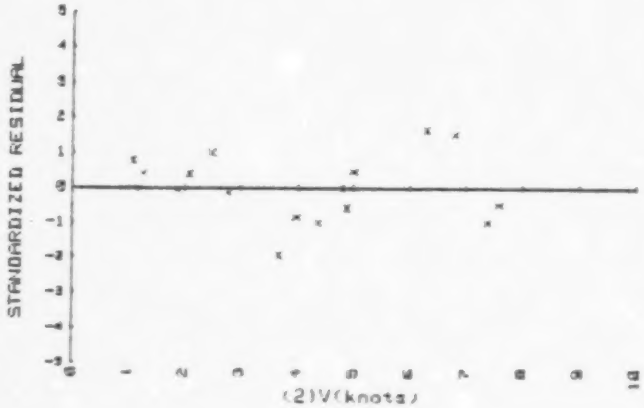


```
*****************************************************************************
MULTIPLE LINEAR REGRESSION ON DATA SET:

                 1252C TOWED RESISTANCE TESTS OF 140' WTGB
*****************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable(s) = (19)SIG**
                                    (13)V*

                                                         STANDARD      COEFF. OF
VARIABLE        N          MEAN          VARIANCE        DEVIATION     VARIATION


SIG**          17      126.90959        948.66793        30.80045      24.26960
V*             17        1.04549           .35579          .59649      57.05321
R*             17        6.67658          8.77822         2.96281      44.37609



                         CORRELATION MATRIX


                        V*          R*
SIG**            .0736498    .2506746
V*                           [illegible]



                           ANALYSIS OF VARIANCE TABLE


SOURCE              DF         SUM OF SQUARES            MEAN SQUARE        F-VALUE


TOTAL               16             140.45147
REGRESSION           2             111.47170              55.73585           26.93
 SIG**               1               8.82565               8.82565            4.26
 V*                  1             102.64605             102.64605           49.59
RESIDUAL            14              28.97977               2.06998

R-SQUARED =  .79367
STANDARD ERROR OF ESTIMATE = 1.43874363931



                 REGRESSION COEFFICIENTS              STANDARD ERROR
VARIABLE       STD. FORMAT            E-FORMAT      REG. COEFFICIENT      T-VALUE


'CONSTANT'         -.06446 -.644568465587E-01             1.60979           -.04
SIG**               .01804  .180402321142E-01              .01171           1.54
V*                 4.25787  .425787193061E+01              .60465           7.04


                                     95 % CONFIDENCE INTERVAL
                   COEFFICIENT         LOWER LIMIT         UPPER LIMIT

'CONSTANT'            -.06446            -3.30301             3.17409
SIG**                  .01804            -.00552              .04160
```

```
                         TABLE OF RESIDUALS


                                                               STANDARDIZED
OBS#      OBSERVED Y      PREDICTED Y           RESIDUAL        RESIDUAL         SIGNIF.
   1         3.69338          4.89639           -1.20301         -.83615
   2         6.88864          6.24260             .64604          .44903
   3         5.27279          3.85649            1.41629          .98440
   4         3.77670          3.93449            -.15779         -.10967
   5         7.25477          7.28649            -.03172         -.02205
   6         4.54412          7.31328           -2.76915        -1.92470
   7         5.27523          5.47357            -.19834         -.13786
   8        12.78833         10.44481            2.34352         1.62886
   9        13.23067         11.06346            2.16720         1.50632
  10         4.88409          3.75819            1.12590          .78255
  11         4.57051          3.98576             .58475          .40643
  12         7.24097          8.05562            -.81464         -.56622
  13         4.21372          4.27889            -.06517         -.04529
  14        10.37184         11.07318            -.70133         -.48746
  15         5.36844          4.83577             .53268          .37024
  16         8.52555          9.94823           -1.42268         -.98883
  17         5.60212          7.05466           -1.45255        -1.00959


Durbin-Watson Statistic: 1.26811239329
```



1252C TOWED RESISTANCE TESTS OF 140' WTGB



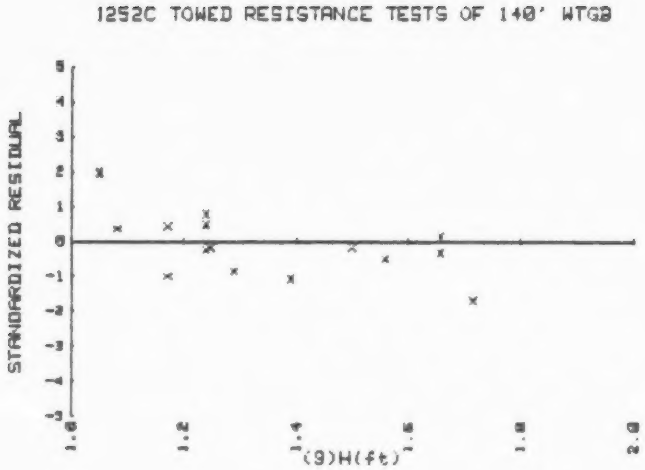
1252C TOWED RESISTANCE TESTS OF 140' WTGB

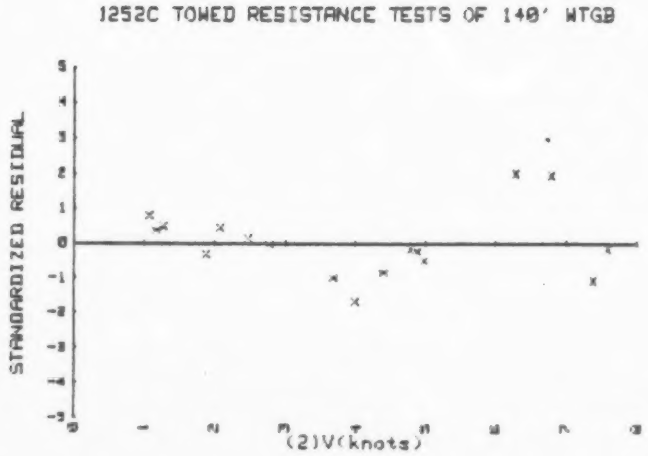
```
*********************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                   1252C TOWED RESISTANCE TESTS OF 140' WTGB
*********************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (14)V**



                                                       STANDARD     COEFF. OF
VARIABLE      N             MEAN          VARIANCE       DEVIATION      VARIATION
V**           17          .20315            .01226          .11072       54.50212
R*            17         6.67658           8.77822         2.96281       44.37609

CORRELATION =   .81067
```

```
SELECTED DEGREE OF REGRESSION =  2
R-SQUARED =   .70339
STANDARD ERROR OF ESTIMATE = 1.72500068159


                        ANALYSIS OF VARIANCE TABLE

SOURCE           DF        SUM OF SQUARES          MEAN SQUARE        F-VALUE

TOTAL            16            140.45147
REGRESSION        2             98.79269              49.39634          16.60
X^1               1             92.30255              92.30255          31.02
X^2               1              6.49014               6.49014           2.18
RESIDUAL         14             41.65878               2.97563


                REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE        STD. FORMAT         E-FORMAT     REG. COEFFICIENT      T-VALUE

'CONSTANT'          4.37585  .437584784265E+01           1.68373        2.60
 X^1               -4.36074 -.436073532414E+01          18.06616        -.24
 X^2               60.34369  .603436872254E+02          40.85961        1.48


                                   95 % CONFIDENCE INTERVAL
                 COEFFICIENT         LOWER LIMIT        UPPER LIMIT

'CONSTANT'          4.37585              .76370            7.98799
 X^1               -4.36074           -43.11854           34.39707
 X^2               60.34369           -27.31352          148.00090
```

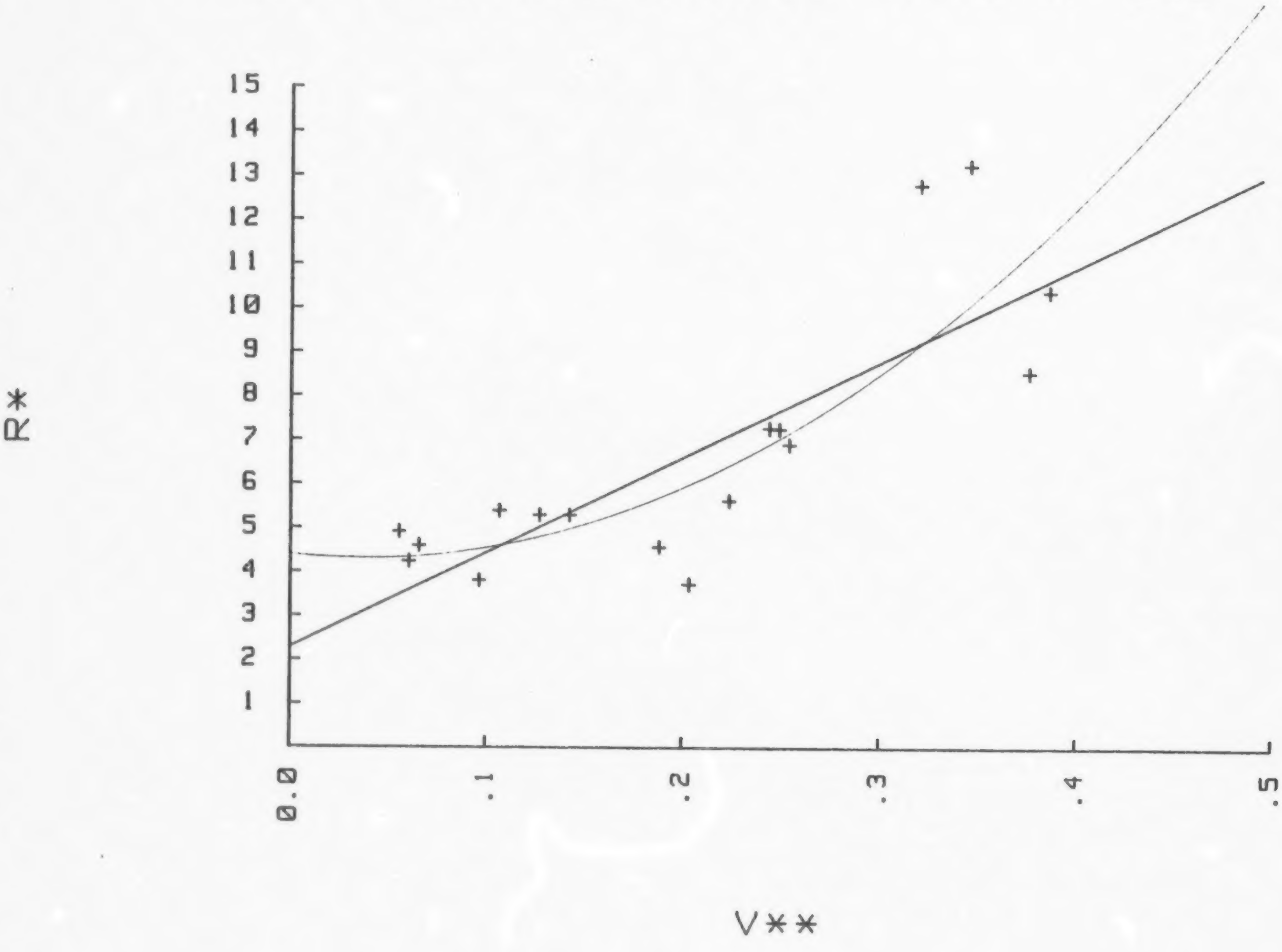
```
SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .65718
STANDARD ERROR OF ESTIMATE = 1.79162715827


                             ANALYSIS OF VARIANCE TABLE


SOURCE             DF         SUM OF SQUARES           MEAN SQUARE         F-VALUE

TOTAL              16              140.45147
REGRESSION          1               92.30255               92.30255          28.76
X^1                 1               92.30255               92.30255          28.76
RESIDUAL           15               48.14892                3.20993


                  REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE         STD. FORMAT            E-FORMAT     REG. COEFFICIENT      T-VALUE

'CONSTANT'           2.26968   .226967790223E+01               .92962         2.44
 X^1                21.69289   .216928912936E+02              4.04537         5.36


                                     95 % CONFIDENCE INTERVAL
                  COEFFICIENT         LOWER LIMIT        UPPER LIMIT

'CONSTANT'            2.26968              .28774            4.25162
 X^1                 21.69289            13.06824           30.31754
```

```
                          TABLE OF RESIDUALS


                                                               STANDARDIZED
OBS#       OBSERVED Y        PREDICTED Y          RESIDUAL       RESIDUAL       SIGNIF.
   1          3.69338            6.68958          -2.99620       -1.67233
   2          6.88864            7.79456           -.90592        -.50564
   3          5.27279            5.03212            .24067         .13433
   4          3.77670            4.36913           -.59243        -.33067
   5          7.25477            7.57356           -.31879        -.17793
   6          4.54412            6.35809          -1.81396       -1.01247
   7          5.27523            5.36361           -.08838        -.04933
   8         12.78833            9.23102           3.55730        1.98551
   9         13.23067            9.78351           3.44716        1.92404
  10          4.88409            3.48515           1.39894         .78082
  11          4.57051            3.70615            .86436         .48245
  12          7.24097            7.68406           -.44309        -.24731
  13          4.21372            3.59565            .61807         .34498
  14         10.37184           10.66749           -.29565        -.16502
  15          5.36844            4.59013            .77832         .43442
  16          8.52555           10.44650          -1.92095       -1.07218
  17          5.60212            7.13157          -1.52945        -.85367

Durbin-Watson Statistic: .966337645053
```


1252C TOWED RESISTANCE TESTS OF 140' WTGB


1252C TOWED RESISTANCE TESTS OF 140' WTGB

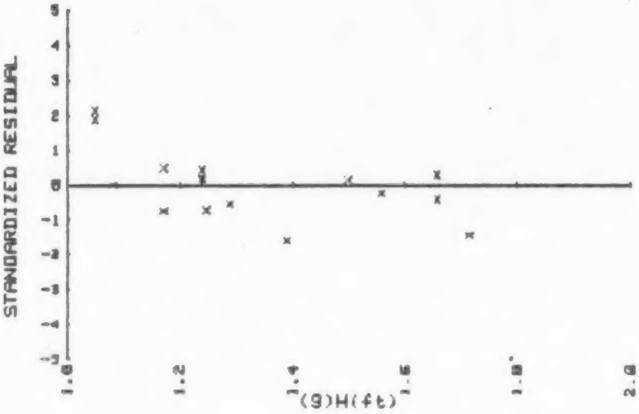
1252C TOWED RESISTANCE TESTS OF 140´ WTGB



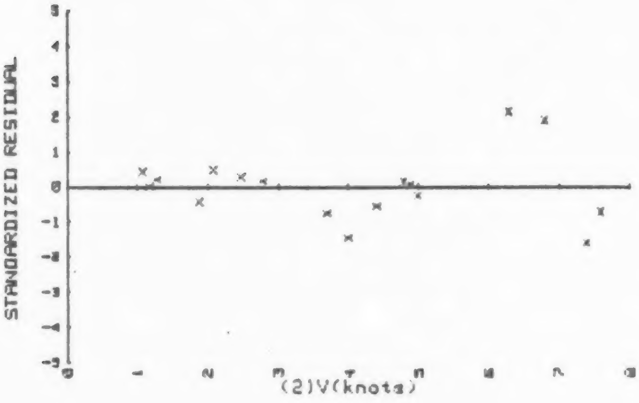
```
*****************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                  1252C TOWED RESISTANCE TESTS OF 140' WTGB
*****************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (22)V******



                                                    STANDARD     COEFF. OF
VARIABLE       N          MEAN          VARIANCE       DEVIATION     VARIATION
V******       17        .05281            .00240          .04896      92.70501
R*            17       6.67658           8.77822         2.96281      44.37609

CORRELATION =    .83795


SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .70216
STANDARD ERROR OF ESTIMATE = 1.66997305288


                          ANALYSIS OF VARIANCE TABLE


SOURCE              DF        SUM OF SQUARES          MEAN SQUARE        F-VALUE

TOTAL               16           140.45147
REGRESSION           1            98.61932             98.61932          35.36
X^1                  1            98.61932             98.61932          35.36
RESIDUAL            15            41.83215              2.78881


                 REGRESSION COEFFICIENTS         STANDARD ERROR
VARIABLE        STD. FORMAT           E-FORMAT   REG. COEFFICIENT        T-VALUE

'CONSTANT'          3.99854  .399853614265E+01              .60569          6.60
 X^1               50.71309  .507130928944E+02             8.52803          5.95


                                   95 % CONFIDENCE INTERVAL
                 COEFFICIENT       LOWER LIMIT       UPPER LIMIT

'CONSTANT'          3.99854           2.70722           5.28985
 X^1               50.71309          32.53150          68.89469
```

```
                              TABLE OF RESIDUALS

                                                              STANDARDIZED
OBS#      OBSERVED Y       PREDICTED Y          RESIDUAL        RESIDUAL       SIGNIF.
   1         3.69338           6.10382          -2.41044        -1.44340
   2         6.88864           7.28804           -.39940         -.23917
   3         5.27279           4.82091            .45187          .27059
   4         3.77670           4.47354           -.69684         -.41728
   5         7.25477           7.03014            .22463          .13451
   6         4.54412           5.79987          -1.25575         -.75196
   7         5.27523           5.03013            .24511          .14677
   8        12.78833           9.22096           3.56737         2.13619          **
   9        13.23067          10.08281           3.14786         1.88498
  10         4.88409           4.15775            .72634          .43494
  11         4.57051           4.22091            .34960          .20935
  12         7.24097           7.15778            .08319          .04982
  13         4.21372           4.18801            .02571          .01540
  14        10.37184          11.59861          -1.22677         -.73460
  15         5.36844           4.57880            .78964          .47285
  16         8.52555          11.20387          -2.67832        -1.60381
  17         5.60212           6.54593           -.94381         -.56517

Durbin-Watson Statistic: 1.1795922068
```

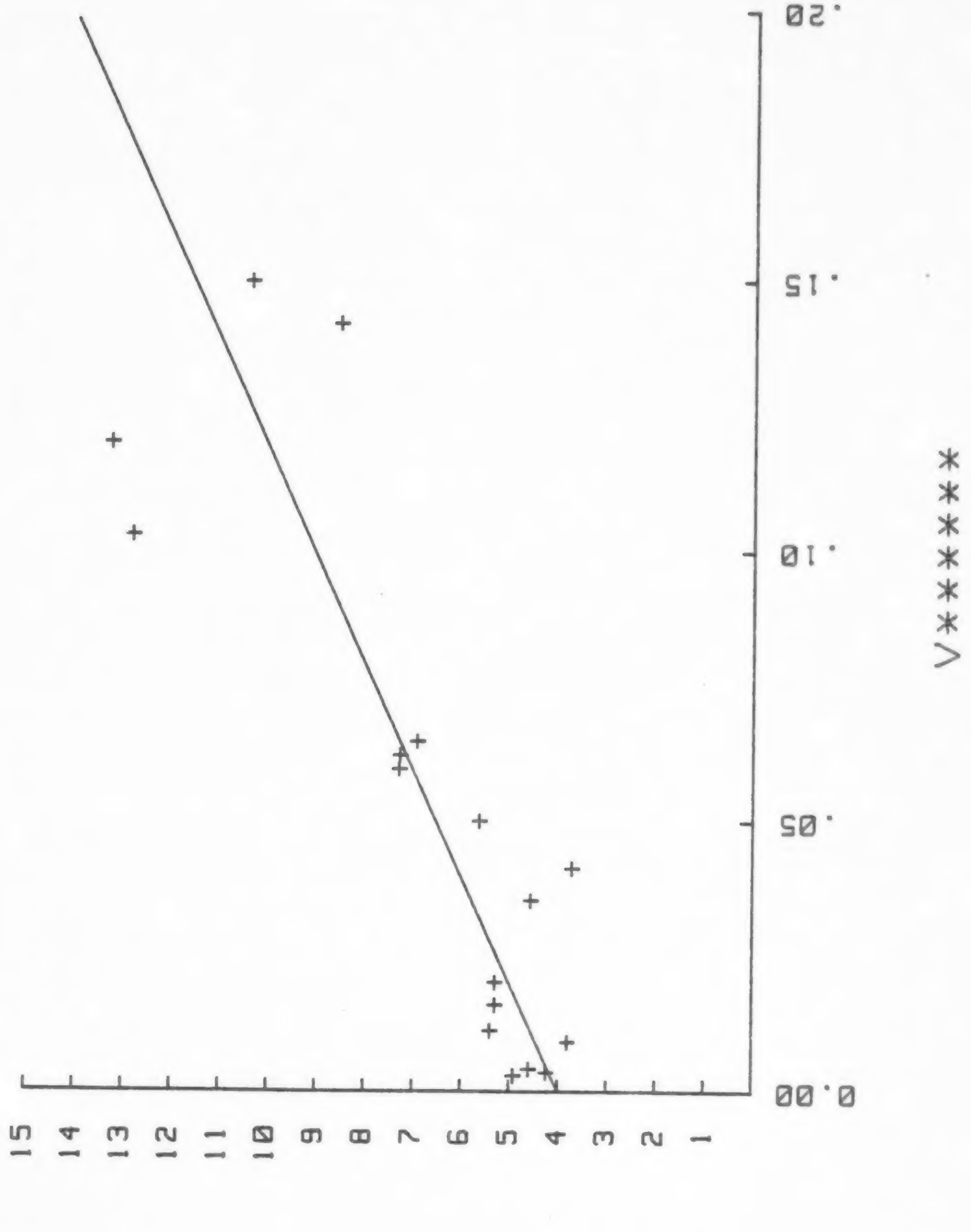
1252C TOWED RESISTANCE TESTS OF 140' WTGB



1252C TOWED RESISTANCE TESTS OF 140' WTGB

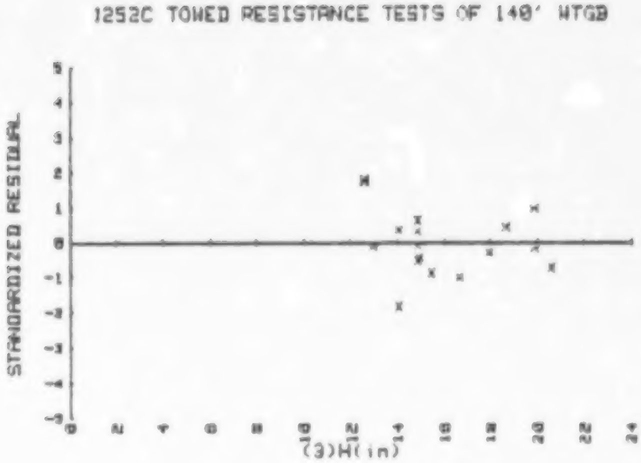


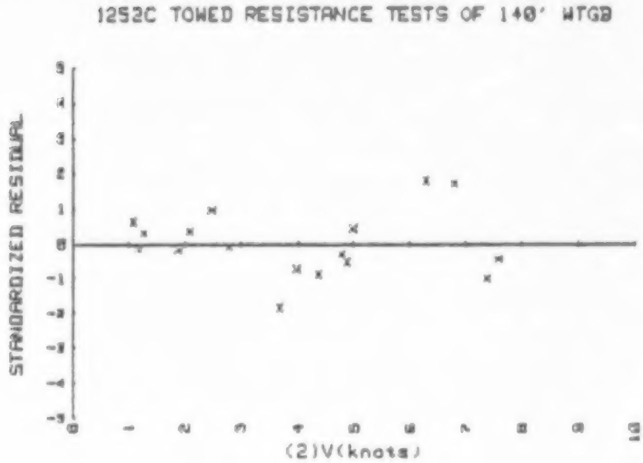
1252C TOWED RESISTANCE TESTS OF 140' WTGB

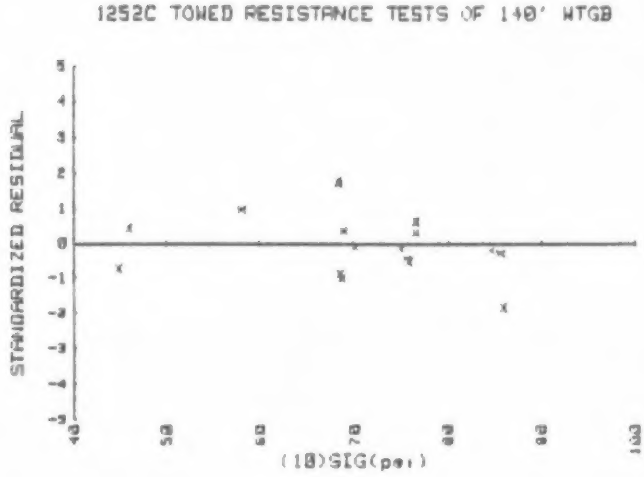


```
**********************************************************************************
MULTIPLE LINEAR REGRESSION ON DATA SET:

                    1252C TOWED RESISTANCE TESTS OF 140' WTGB
**********************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable(s) = (19)SIG**
                                    (14)V**

                                                            STANDARD     COEFF. OF
VARIABLE        N             MEAN           VARIANCE       DEVIATION    VARIATION


SIG**          17        126.90959          948.66793        30.80045     24.26960
V**            17           .20315             .01226          .11072     54.50212
R*             17          6.67658            8.77822         2.96281     44.37609


                         CORRELATION MATRIX


                    V**          R*
SIG**          -.0427260    .2506746
V**                         .8106693


                            ANALYSIS OF VARIANCE TABLE


SOURCE               DF        SUM OF SQUARES            MEAN SQUARE       F-VALUE


TOTAL                16             140.45147
REGRESSION            2             103.75656               51.87828         19.79
 SIG**                1               8.82565                8.82565          3.37
 V**                  1              94.93091               94.93091         36.22
RESIDUAL             14              36.69491                2.62106

R-SQUARED =  .73874
STANDARD ERROR OF ESTIMATE = 1.61897025246



                   REGRESSION COEFFICIENTS           STANDARD ERROR
 VARIABLE       STD. FORMAT            E-FORMAT     REG. COEFFICIENT       T-VALUE


'CONSTANT'        -1.28613 -.128612842849E+01              1.89710          -.68
SIG**               .02750  .274953020390E-01               .01315          2.09
V**               22.01969  .220196888375E+02              3.65886          6.02


                                       95 % CONFIDENCE INTERVAL
                  COEFFICIENT         LOWER LIMIT          UPPER LIMIT

'CONSTANT'           -1.28613    E-27 -5.10267              2.53041
SIG**                  .02750           .00107               .05396
```

```
                              TABLE OF RESIDUALS


                                                                      STANDARDIZED
OBS#        OBSERVED Y        PREDICTED Y            RESIDUAL          RESIDUAL        SIGNIF.
   1           3.69338           4.86186             -1.16847           -.72174
   2           6.88864           6.19483               .69381            .42855
   3           5.27279           3.74248              1.53031            .94524
   4           3.77670           4.08872              -.31202           -.19273
   5           7.25477           7.72801              -.47324           -.29231
   6           4.54412           7.51247             -2.96835          -1.83348
   7           5.27523           5.43935              -.16412           -.10137
   8          12.78833           9.91684              2.87149           1.77365
   9          13.23067          10.47765              2.75302           1.70047
  10           4.88409           3.86623              1.01786            .62871
  11           4.57051           4.09055               .47995            .29646
  12           7.24097           8.08836              -.84738           -.52341
  13           4.21372           4.45168              -.23796           -.14698
  14          10.37184          11.07762              -.70578           -.43594
  15           5.36844           4.79415               .57429            .35473
  16           8.52555          10.15287             -1.62732          -1.00516
  17           5.60212           7.01820             -1.41608           -.87468


Durbin-Watson Statistic: 1.17424150915
```


1252C TOWED RESISTANCE TESTS OF 140' WTGB

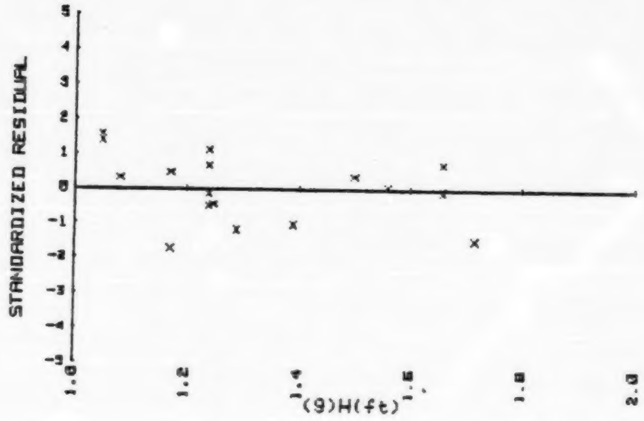

1252C TOWED RESISTANCE TESTS OF 140' WTGB


1252C TOWED RESISTANCE TESTS OF 140' WTGB

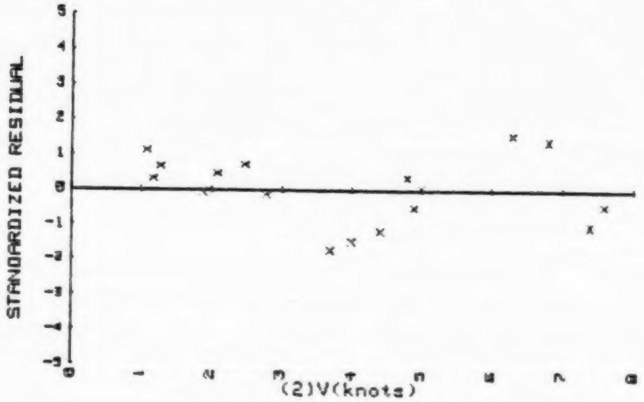
```
********************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                    1252C TOWED RESISTANCE TESTS OF 140' WTGB
********************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (15)V***



                                                          STANDARD      COEFF. OF
VARIABLE        N           MEAN          VARIANCE        DEVIATION      VARIATION
V***           17       20.58614         155.96551         12.48862       60.56517
R*             17        6.67658           8.77822          2.96281       44.37609

CORRELATION =    .91034


SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .82872
STANDARD ERROR OF ESTIMATE = 1.26638684438


                        ANALYSIS OF VARIANCE TABLE

SOURCE            DF       SUM OF SQUARES          MEAN SQUARE          F-VALUE

TOTAL             16           140.45147
REGRESSION         1           116.39543            116.39543            72.58
X^1                1           116.39543            116.39543            72.58
RESIDUAL          15            24.05603              1.60374


                 REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE         STD. FORMAT          E-FORMAT    REG. COEFFICIENT      T-VALUE

'CONSTANT'           2.23059  .223059030852E+01              .60555       3.68
 X^1                  .21597  .215970131708E+00              .02535       8.52


                                   95 % CONFIDENCE INTERVAL
                 COEFFICIENT        LOWER LIMIT        UPPER LIMIT

'CONSTANT'           2.23059             .93957            3.52161
 X^1                  .21597             .16192             .27002
```

```
                            TABLE OF RESIDUALS

                                                                STANDARDIZED
OBS#      OBSERVED Y      PREDICTED Y           RESIDUAL          RESIDUAL        SIGNIF.
   1         3.69338          5.56291           -1.86953          -1.47627
   2         6.88864          6.81921             .06943            .05482
   3         5.27279          4.38655             .88624            .69982
   4         3.77670          3.86912            -.09242           -.07298
   5         7.25477          6.80697             .44780            .35360
   6         4.54412          6.73395           -2.18982          -1.72919
   7         5.27523          5.45556            -.18033           -.14239
   8        12.78833         10.81131            1.97702           1.56115
   9        13.23067         11.49232            1.73835           1.37269
  10         4.88409          3.49754            1.38655           1.09489
  11         4.57051          3.72790             .84261            .66537
  12         7.24097          7.87428            -.63331           -.50009
  13         4.21372          3.81472             .39900            .31507
  14        10.37184         10.92572            -.55387           -.43737
  15         5.36844          4.78655             .58190            .45949
  16         8.52555          9.83506           -1.30951          -1.03405
  17         5.60212          7.10222           -1.50011          -1.18456

Durbin-Watson Statistic: 1.2827488783
```

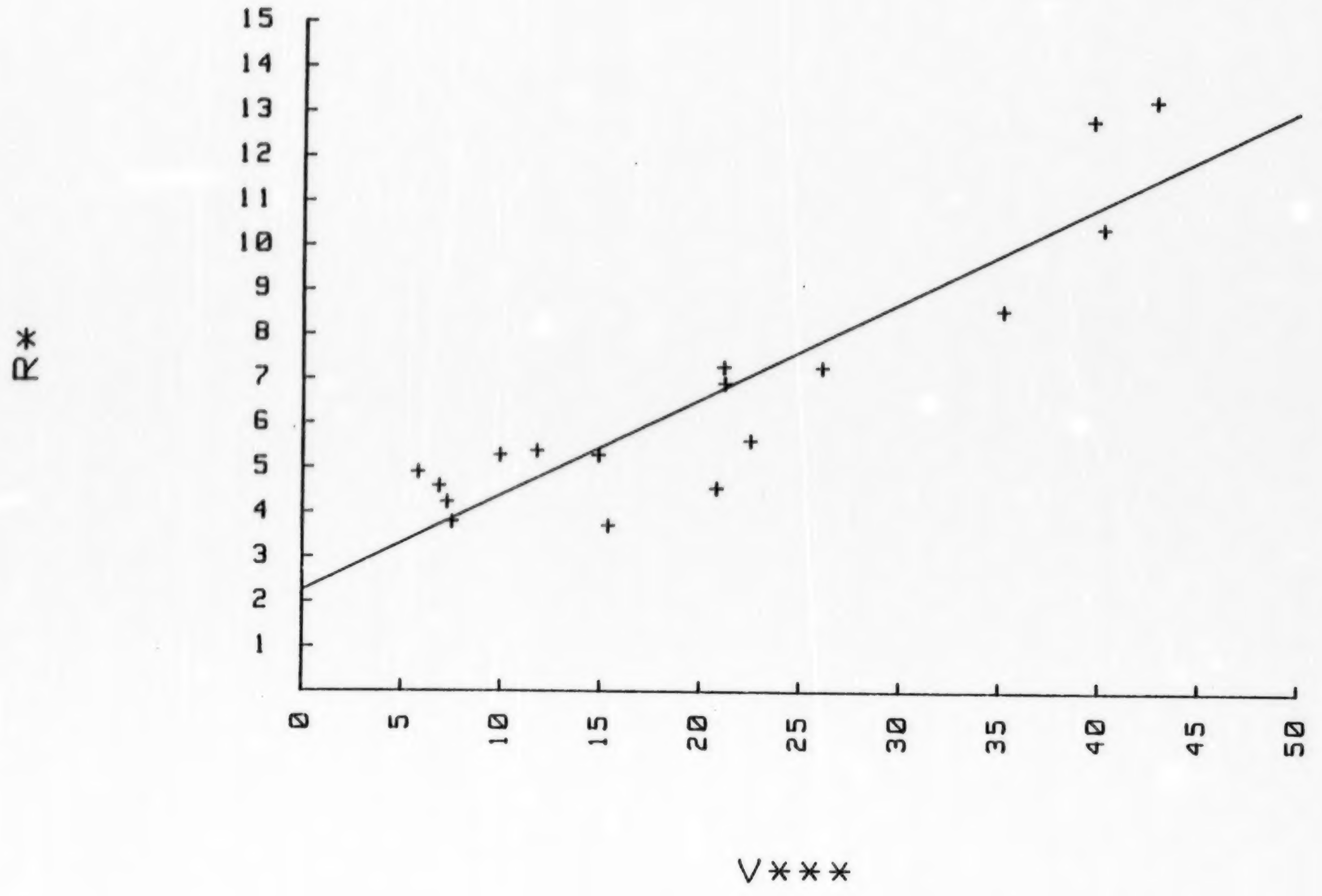
1252C TOWED RESISTANCE TESTS OF 140' WTGB



1252C TOWED RESISTANCE TESTS OF 140' WTGB



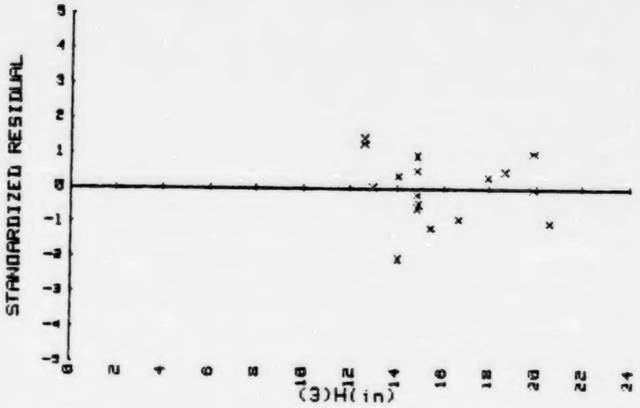
1252C TOWED RESISTANCE TESTS OF 140′ WTGB



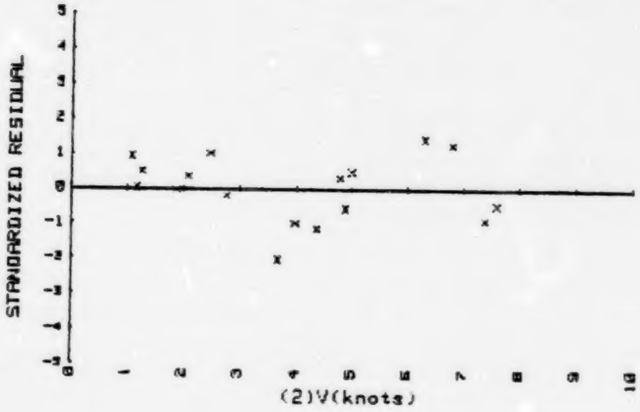
```
***************************************************************************
MULTIPLE LINEAR REGRESSION ON DATA SET:

                   1252C TOWED RESISTANCE TESTS OF 140' WTGB
***************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable(s) = (19)SIG**
                                    (15)V***

                                                          STANDARD     COEFF. OF
VARIABLE        N          MEAN          VARIANCE        DEVIATION    VARIATION

SIG**          17       126.90959       948.66793        30.80045      24.26960
V***           17        20.58614       155.96551        12.48862      60.66517
R*             17         6.67658         8.77822         2.96281      44.37609


                        CORRELATION MATRIX


                V***         R*
SIG**        .1721490     .2506746
V***                      .9103425


                        ANALYSIS OF VARIANCE TABLE

SOURCE           DF        SUM OF SQUARES          MEAN SQUARE        F-VALUE

TOTAL            16            140.45147
REGRESSION        2            117.67328            58.83664           36.16
 SIG**            1              8.92565             8.82565            5.42
 V***             1            108.84762           108.84762           66.90
RESIDUAL         14             22.77819             1.62701

R-SQUARED =   .83782
STANDARD ERROR OF ESTIMATE = 1.27554449066


                    REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE          STD. FORMAT          E-FORMAT     REG. COEFFICIENT      T-VALUE

'CONSTANT'           1.12992   .112991573766E+01         1.38367            .82
SIG**                 .00931   .931438109321E-02          .01051            .89
V***                  .21202   .212015542018E+00          .02592           8.18

                                      95 % CONFIDENCE INTERVAL
                  COEFFICIENT       LOWER LIMIT         UPPER LIMIT

'CONSTANT'           1.12992         -1.65372             3.91355
SIG**                 .00931          -.01183              .03046
```

```
                          TABLE OF RESIDUALS


                                                               STANDARDIZED
OBS#       OBSERVED Y      PREDICTED Y          RESIDUAL          RESIDUAL        SIGNIF.
   1          3.69338          4.96407          -1.27069          -.99619
   2          6.88864          6.26896            .61967           .48581
   3          5.27279          3.99999           1.27279           .99784
   4          3.77670          3.83731           -.06061          -.04752
   5          7.25477          6.85233            .40244           .31551
   6          4.54412          7.12558          -2.58146         -2.02381           **
   7          5.27523          5.51027           -.23504          -.18427
   8         12.78833         10.95489           1.83344          1.43738
   9         13.23067         11.62343           1.60724          1.26004
  10          4.88409          3.70113           1.18296           .92741
  11          4.57051          3.92727            .64324           .50428
  12          7.24097          7.98417           -.74320          -.58265
  13          4.21372          4.17284            .04088           .03205
  14         10.37184         10.96648           -.59464          -.46618
  15          5.36844          4.90092            .46752           .36653
  16          8.52555          9.65852          -1.13296          -.88822
  17          5.60212          7.05370          -1.45158         -1.13801


Durbin-Watson Statistic: 1.40199702301
```

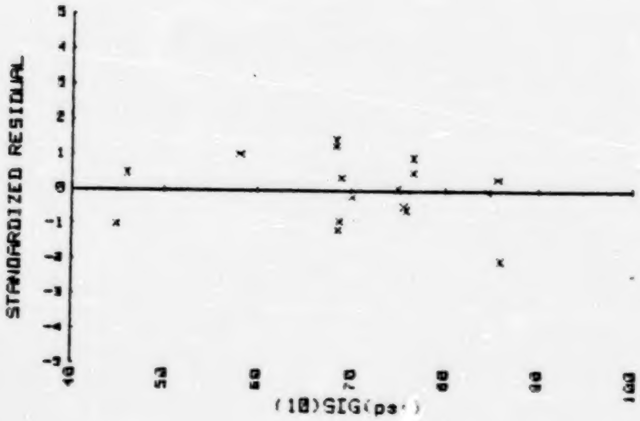
1252C TOWED RESISTANCE TESTS OF 140' WTGB



1252C TOWED RESISTANCE TESTS OF 140' WTGB

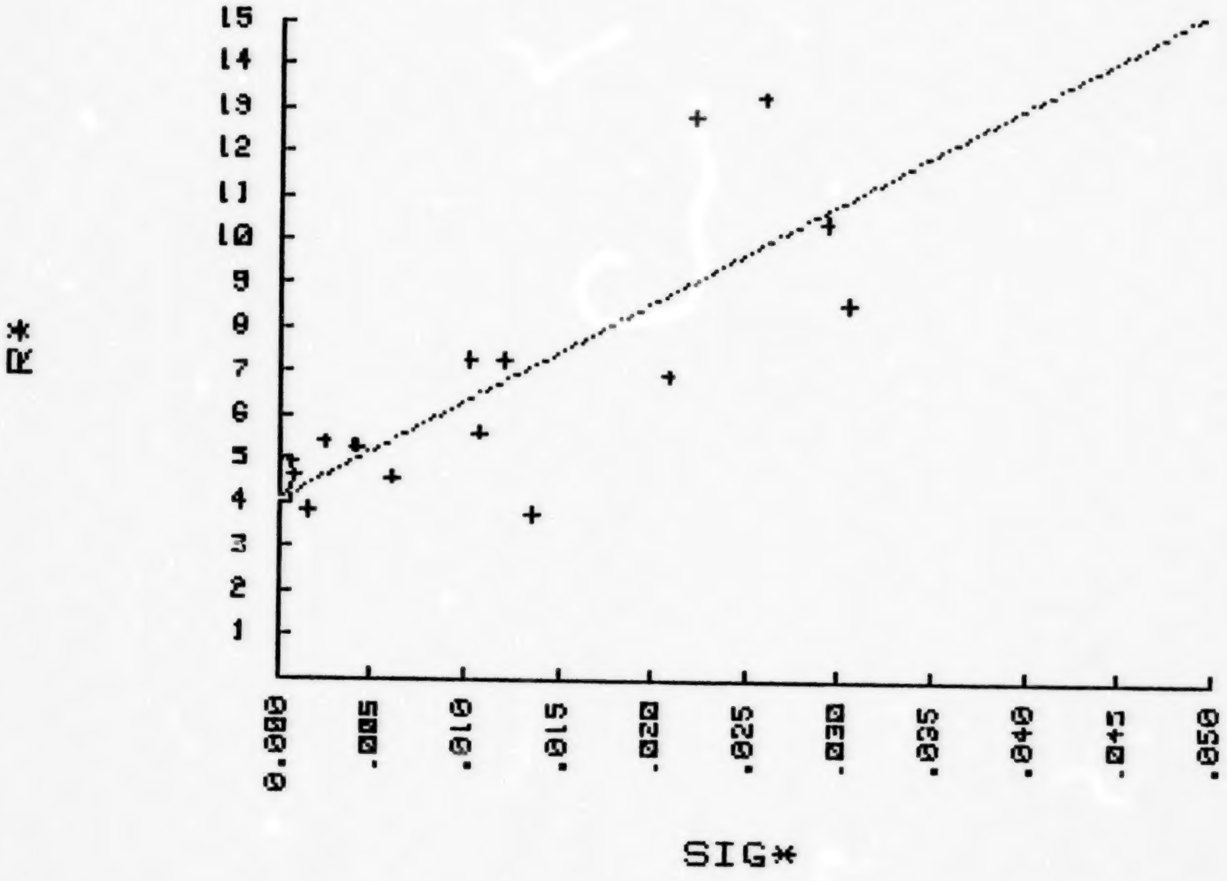


1252C TOWED RESISTANCE TESTS OF 140' WTGB

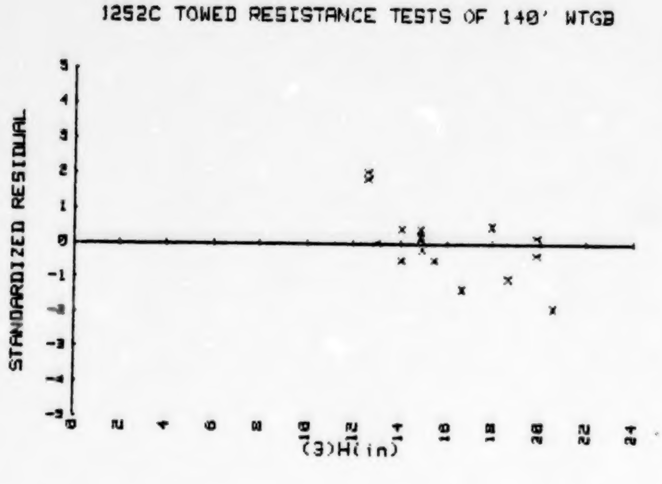


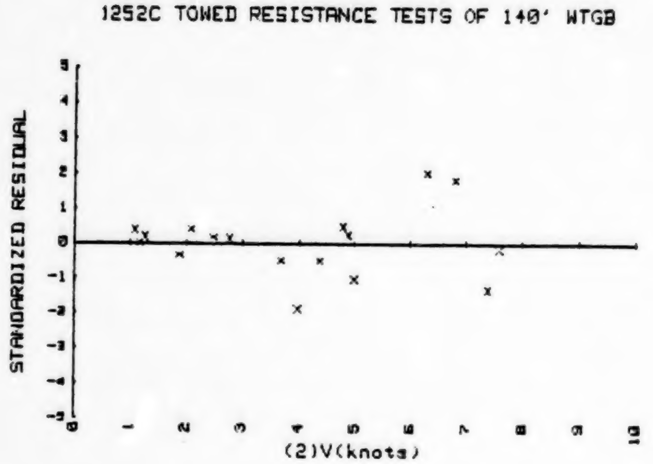
```
****************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                    1252C TOWED RESISTANCE TESTS OF 140' WTGB
****************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (18)SIG*




                                                            STANDARD     COEFF. OF
VARIABLE       N           MEAN           VARIANCE         DEVIATION     VARIATION
SIG*          17         .01158             .00011            .01050      90.68847
R*            17        6.67658            8.77822           2.96281      44.37609

CORRELATION =   .80059


SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .64095
STANDARD ERROR OF ESTIMATE = 1.83356128521


                          ANALYSIS OF VARIANCE TABLE


SOURCE            DF        SUM OF SQUARES         MEAN SQUARE          F-VALUE

TOTAL             16           140.45147
REGRESSION         1            90.02226            90.02226            26.78
X^1                1            90.02226            90.02226            26.78
RESIDUAL          15            50.42920             3.36195


                  REGRESSION COEFFICIENTS           STANDARD ERROR
VARIABLE          STD. FORMAT          E-FORMAT   REG. COEFFICIENT      T-VALUE

'CONSTANT'          4.06103  .406103154428E+01             .67324         6.03
 X^1              225.91469  .225914691858E+03           43.65811         5.17


                                  95 % CONFIDENCE INTERVAL
                 COEFFICIENT        LOWER LIMIT        UPPER LIMIT

'CONSTANT'          4.06103            2.62570            5.49636
 X^1              225.91469          132.83641          318.99298
```

1252C TOWED RESISTANCE TESTS OF 140′ WTGB



```
                              TABLE OF RESIDUALS

                                                                STANDARDIZED
OBS#          OBSERVED Y        PREDICTED Y            RESIDUAL       RESIDUAL        SIGNIF.
   1             3.69338            7.15055            -3.45717       -1.88550
   2             6.88864            8.77877            -1.89014       -1.03085
   3             5.27279            4.99412              .27867         .15198
   4             3.77670            4.43064             -.65394        -.35665
   5             7.25477            6.39126              .86351         .47095
   6             4.54412            5.44142             -.89729        -.48937
   7             5.27523            5.03106              .24417         .13317
   8            12.78833            9.09359             3.69474        2.01506          **
   9            13.23067            9.92411             3.30656        1.80335
  10             4.88409            4.19800              .68609         .37419
  11             4.57051            4.25233              .31818         .17353
  12             7.24097            6.80687              .43410         .23675
  13             4.21372            4.22772             -.01400        -.00764
  14            10.37184           10.68941             -.31757        -.17320
  15             5.36844            4.61597              .75247         .41039
  16             8.52555           10.96491            -2.43936       -1.33039
  17             5.60212            6.51114             -.90902        -.49577

Durbin-Watson Statistic: .947377163459
```

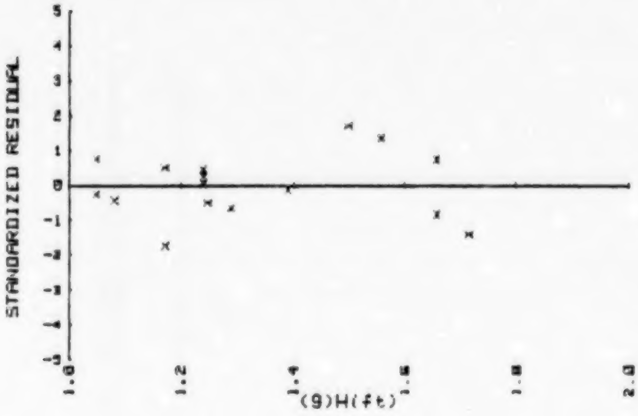

1252C TOWED RESISTANCE TESTS OF 140' WTGB


1252C TOWED RESISTANCE TESTS OF 140' WTGB

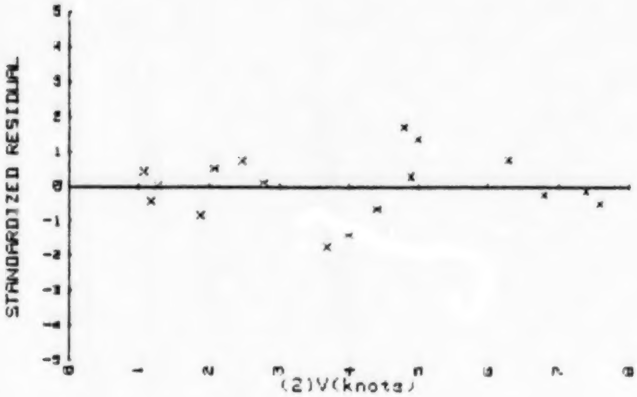
```
********************************************************************************

NON-LINEAR REGRESSION ON DATA SET:

                  1252C TOWED RESISTANCE TESTS OF 140' WTGB

********************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable(s) = (14)V**
                                    (20)L/H

********************************************************************************

Delta(Convergence criteria)=  .001

THE INITIAL VALUES OF PARAMETERS ARE :
          PARAMETER 1 = 4
          PARAMETER 2 = .01
          PARAMETER 3 = 2
          PARAMETER 4 = 2



********************************************************************************

THE ESTIMATED PARAMETER VALUES AFTER 124 ITERATIONS ARE :
          PARAMETER  1=        4.3815343 ( 4.3815343414E+00)
          PARAMETER  2=         .0000098 ( 9.8304848280E-06)
          PARAMETER  3=        2.1114388 ( 2.1114388450E+00)
          PARAMETER  4=        3.3149234 ( 3.3149234479E+00)

********************************************************************************

           THE INITIAL VALUE OF SUM OF SQUARED RESIDUALS = 344.531717561
           AFTER 124 ITERATIONS THE SUM OF SQUARED RESIDUALS= 10.5881101974
           APPROXIMATE STANDARD ERROR FROM SQUARED RESIDUALS= .902479925086
```

```
                         TABLE OF RESIDUALS


                                                            STANDARDIZED
OBS#     OBSERVED Y       PREDICTED Y          RESIDUAL        RESIDUAL      SIGNIF.
  1        3.69338          4.96145            -1.26807        -1.40510
  2        6.88864          5.66179             1.22685         1.35942
  3        5.27279          4.62261              .65018          .72044
  4        3.77670          4.51658             -.73988         -.81983
  5        7.25477          5.71441             1.54036         1.70681
  6        4.54412          6.11005            -1.56592        -1.73513
  7        5.27523          5.18072              .09451          .10473
  8       12.78833         12.10189              .68644          .76061
  9       13.23067         13.45285             -.22218         -.24619
 10        4.88409          4.49268              .39141          .43370
 11        4.57051          4.53969              .03082          .03415
 12        7.24097          6.98653              .25444          .28194
 13        4.21372          4.59146             -.37774         -.41856
 14       10.37184         10.81810             -.44626         -.49448
 15        5.36844          4.90429              .46416          .51431
 16        8.52555          8.64380             -.11825         -.13103
 17        5.60212          6.20239             -.60027         -.66513

Durbin-Watson Statistic: 2.79863163027
```

1252C TOWED RESISTANCE TESTS OF 140' WTGB

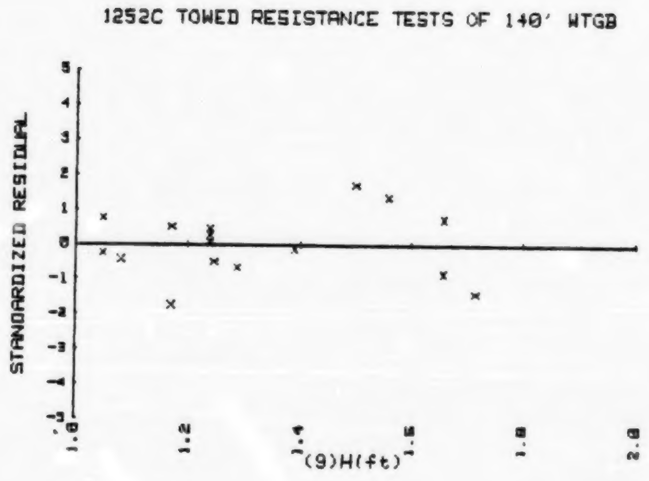


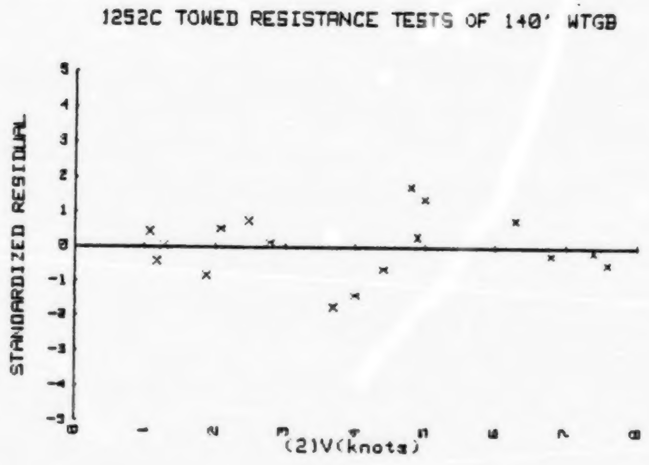
1252C TOWED RESISTANCE TESTS OF 140' WTGB



```
*******************************************************************************

NON-LINEAR REGRESSION ON DATA SET:

                    1252C TOWED RESISTANCE TESTS OF 140' WTGB

*******************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable(s) = (13)V*
                                    (21)B/H

*******************************************************************************

Delta(Convergence criteria)=  .001

THE INITIAL VALUES OF PARAMETERS ARE :
          PARAMETER 1 = 4
          PARAMETER 2 = 1.E-5
          PARAMETER 3 = 2
          PARAMETER 4 = 3



*******************************************************************************

THE ESTIMATED PARAMETER VALUES AFTER 42 ITERATIONS ARE :
          PARAMETER  1=        4.3816126 ( 4.3816125769E+00)
          PARAMETER  2=         .0008239 ( 8.2394588302E-04)
          PARAMETER  3=        2.1115098 ( 2.1115097695E+00)
          PARAMETER  4=        2.2593753 ( 2.2593753449E+00)

*******************************************************************************

          THE INITIAL VALUE OF SUM OF SQUARED RESIDUALS = 200.275657478
          AFTER 42 ITERATIONS THE SUM OF SQUARED RESIDUALS= 10.5881100982
          APPROXIMATE STANDARD ERROR FROM SQUARED RESIDUALS= .902479920861
```

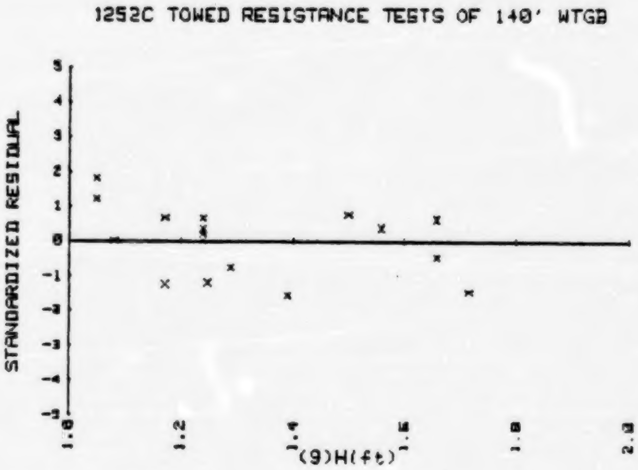
```
                              TABLE OF RESIDUALS

                                                               STANDARDIZED
OBS#       OBSERVED Y        PREDICTED Y           RESIDUAL        RESIDUAL       SIGNIF.
   1          3.69338            4.96146           -1.26808        -1.40510
   2          6.88864            5.66176            1.22688         1.35945
   3          5.27279            4.62265             .65014          .72039
   4          3.77670            4.51664            -.73994         -.81989
   5          7.25477            5.71438            1.54039         1.70684
   6          4.54412            6.11004           -1.56592        -1.73513
   7          5.27523            5.18073             .09450          .10471
   8         12.78833           12.10207             .68626          .76042
   9         13.23067           13.45309            -.22242         -.24646
  10          4.88409            4.49274             .39135          .43363
  11          4.57051            4.53975             .03076          .03409
  12          7.24097            6.98650             .25447          .28197
  13          4.21372            4.59152            -.37780         -.41862
  14         10.37184           10.81811            -.44627         -.49449
  15          5.36844            4.90432             .46413          .51428
  16          8.52555            8.64374            -.11818         -.13096
  17          5.60212            6.20237            -.60025         -.66511

Durbin-Watson Statistic: 2.79872207518
```


1252C TOWED RESISTANCE TESTS OF 140' WTGB
STANDARDIZED RESIDUAL
5
4
3
2
1
0
-1
-2
-3
-4
-5
1.0
1.2
1.4
1.6
1.8
2.0
(9)H(ft)

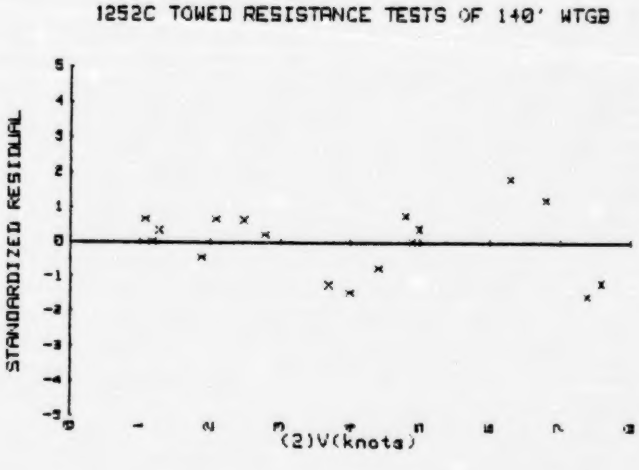

1252C TOWED RESISTANCE TESTS OF 140' WTGB
STANDARDIZED RESIDUAL
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
1
2
3
4
5
6
7
8
(2)V(knots)

```
********************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                    1252C TOWED RESISTANCE TESTS OF 140' WTGB
********************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (17)V*****



                                                          STANDARD      COEFF. OF
VARIABLE      N            MEAN           VARIANCE        DEVIATION     VARIATION
V*****       17         8.92401           81.71213          9.03948     101.29394
R*           17         6.67658            8.77822          2.96281      44.37609

CORRELATION =   .92604

SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .85756
STANDARD ERROR OF ESTIMATE = 1.15488070025


                         ANALYSIS OF VARIANCE TABLE

SOURCE              DF        SUM OF SQUARES          MEAN SQUARE         F-VALUE

TOTAL               16            140.45147
REGRESSION           1            120.44523            120.44523           90.31
X^1                  1            120.44523            120.44523           90.31
RESIDUAL            15             20.00624              1.33375

                  REGRESSION COEFFICIENTS        STANDARD ERROR
VARIABLE          STD. FORMAT         E-FORMAT   REG. COEFFICIENT        T-VALUE

'CONSTANT'          3.96794   .396794037273E+01            .39962           9.93
 X^1                 .30352   .303522958236E+00            .03194           9.50


                                  95 % CONFIDENCE INTERVAL
                  COEFFICIENT      LOWER LIMIT          UPPER LIMIT

'CONSTANT'          3.96794          3.11595              4.81993
 X^1                 .30352           .23543               .37162
```

```
                         TABLE OF RESIDUALS


                                                                   STANDARDIZED
 OBS#       OBSERVED Y        PREDICTED Y           RESIDUAL         RESIDUAL        SIGNIF.
    1          3.69338           5.36920            -1.67582         -1.45108
    2          6.88864           6.46296              .42568           .36859
    3          5.27279           4.54146              .73133           .63325
    4          3.77670           4.29921             -.52250          -.45243
    5          7.25477           6.38889              .86589           .74976
    6          4.54412           5.96816            -1.42404         -1.23306
    7          5.27523           5.03119              .24404           .21131
    8         12.78833          10.71790             2.07043          1.79276
    9         13.23067          11.83184             1.39883          1.21123
   10          4.88409           4.13204              .75205           .65119
   11          4.57051           4.19714              .37337           .32330
   12          7.24097           7.22414              .01683           .01457
   13          4.21372           4.20272              .01100           .00953
   14         10.37184          11.73085            -1.35900         -1.17675
   15          5.36844           4.61228              .75617           .65476
   16          8.52555          10.33467            -1.80912         -1.56650
   17          5.60212           6.45724             -.85513          -.74045

Durbin-Watson Statistic: 1.71711052273
```

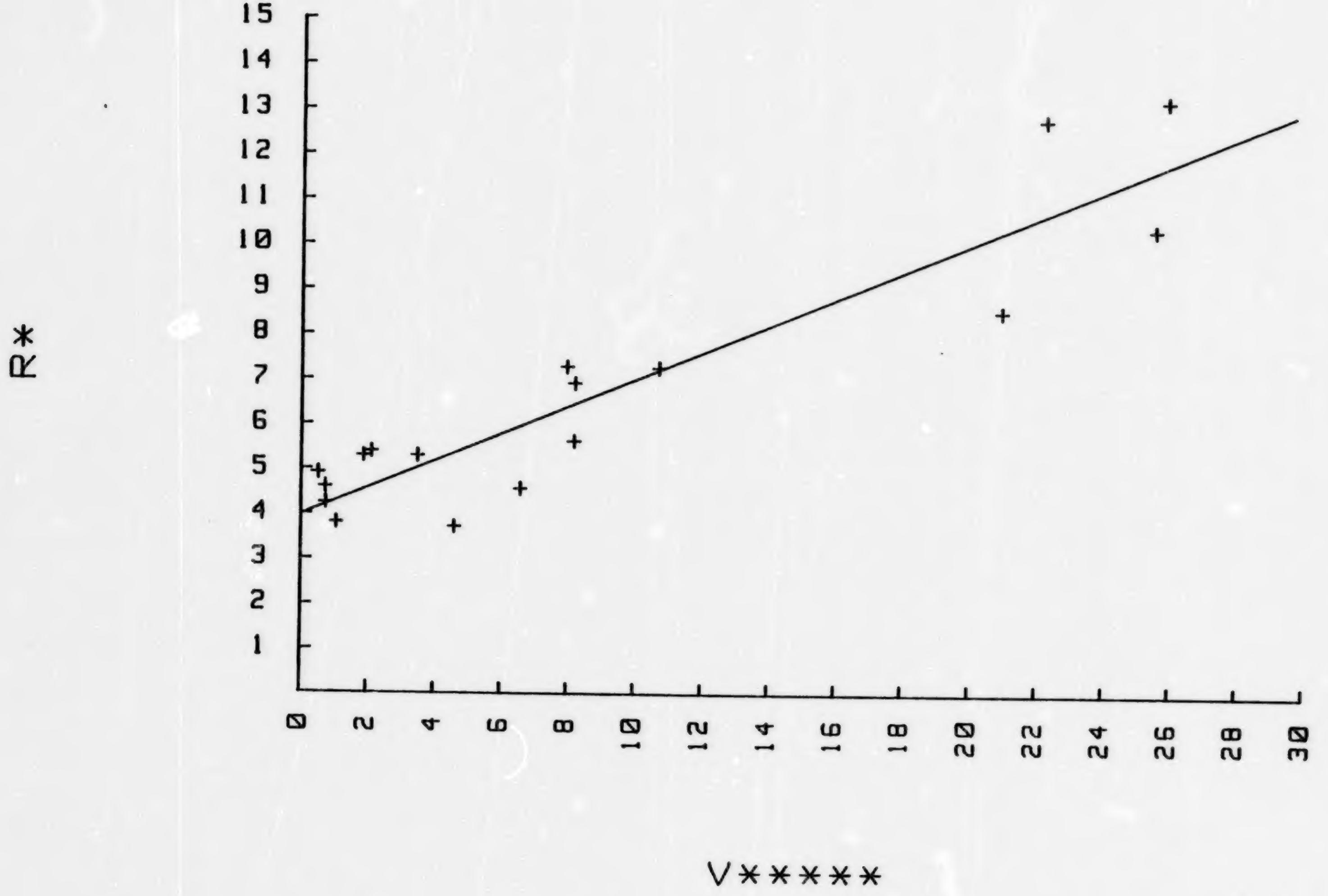


1252C TOWED RESISTANCE TESTS OF 140' WTGB



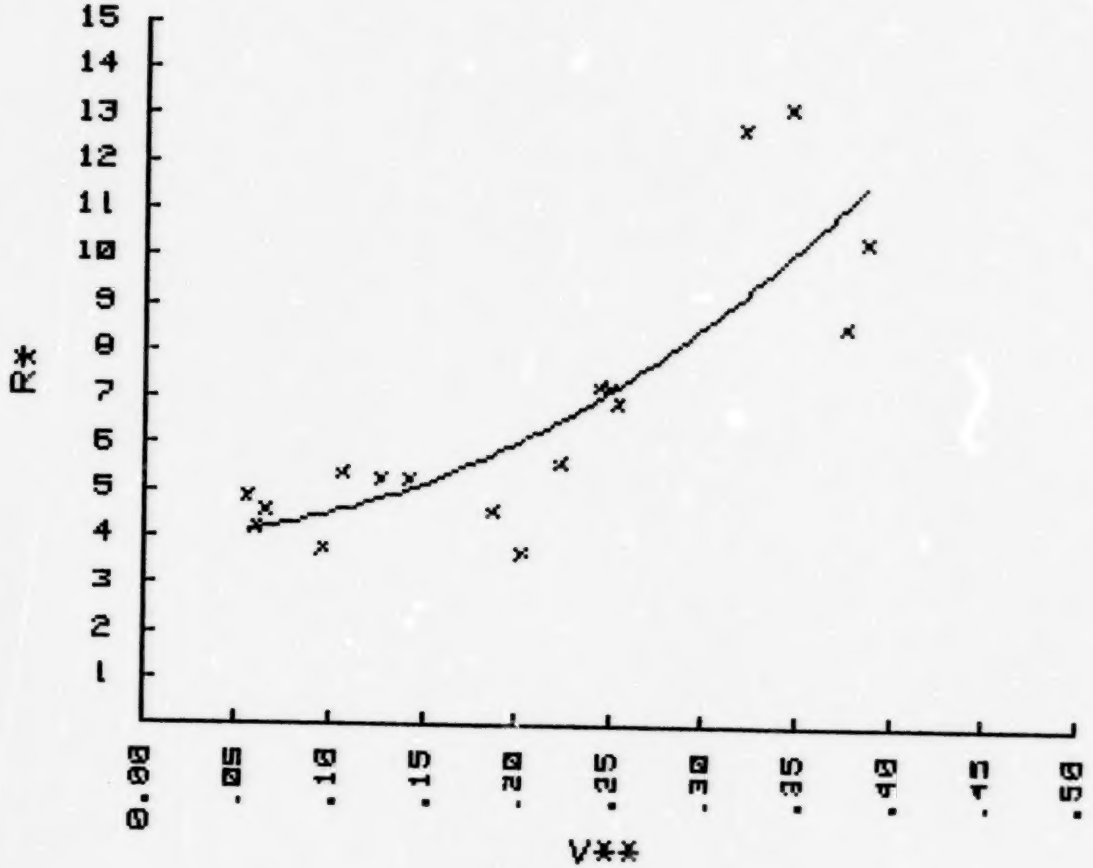
1252C TOWED RESISTANCE TESTS OF 140' WTGB

1252C TOWED RESISTANCE TESTS OF 140′ WTGB



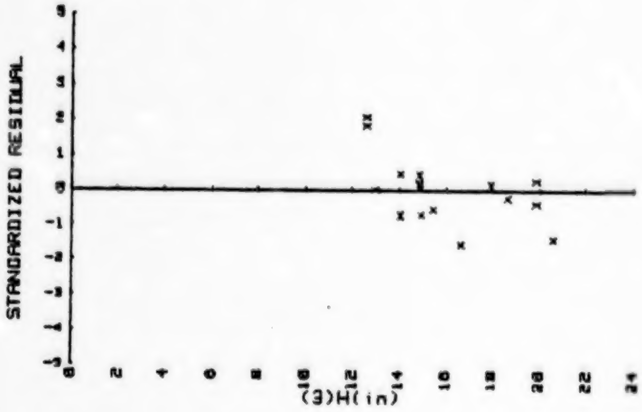
```
********************************************************************************

REGRESSION MODELING ON DATA SET:
                    1252C TOWED RESISTANCE TESTS OF 140' WTGB

********************************************************************************


--where:  Dependent variable = (12)R*
          Independent variable = (14)V**

THE STANDARD NON-LINEAR REGRESSION MODEL SELECTED = Y=A*X^B+C

********************************************************************************

Delta(Convergence criteria)=  .05

THE INITIAL VALUES OF PARAMETERS ARE :
          PARAMETER 1 = 18.626770669
          PARAMETER 2 = 1.31683477805
          PARAMETER 3 = 3.95539307318



********************************************************************************

THE ESTIMATED PARAMETER VALUES AFTER 4 ITERATIONS ARE :
           PARAMETER  1=       50.4911197 ( 5.0491119698E+01)
           PARAMETER  2=        1.9958993 ( 1.9958992526E+00)
           PARAMETER  3=        3.9955477 ( 3.9955476715E+00)

********************************************************************************

           THE INITIAL VALUE OF SUM OF SQUARED RESIDUALS = 56.4793941738
           AFTER 4 ITERATIONS THE SUM OF SQUARED RESIDUALS= 41.8326550735
           APPROXIMATE STANDARD ERROR FROM SQUARED RESIDUALS= 1.72859676934

********************************************************************************
```

1252C TOWED RESISTANCE TESTS OF 140' WTGB



```
                              TABLE OF RESIDUALS

                                                                STANDARDIZED
OBS#       OBSERVED Y      PREDICTED Y          RESIDUAL          RESIDUAL         SIGNIF.
   1          3.69338          6.10534          -2.41195          -1.39532
   2          6.88864          7.28908           -.40044           -.23166
   3          5.27279          4.82127            .45151            .26120
   4          3.77670          4.47302           -.69632           -.40283
   5          7.25477          7.03137            .22340            .12924
   6          4.54412          5.80131          -1.25719           -.72729
   7          5.27523          5.03086            .24437            .14137
   8         12.78833          9.21940           3.56893           2.06464           **
   9         13.23067         10.07958           3.15109           1.82292
  10          4.88409          4.15595            .72814            .42123
  11          4.57051          4.21942            .35108            .20310
  12          7.24097          7.15891            .08206            .04747
  13          4.21372          4.18637            .02735            .01582
  14         10.37184         11.59186          -1.22002           -.70579
  15          5.36844          4.57860            .78985            .45693
  16          8.52555         11.19810          -2.67255          -1.54608
  17          5.60212          6.54739           -.94528           -.54685

Durbin-Watson Statistic: 1.17766598822
```

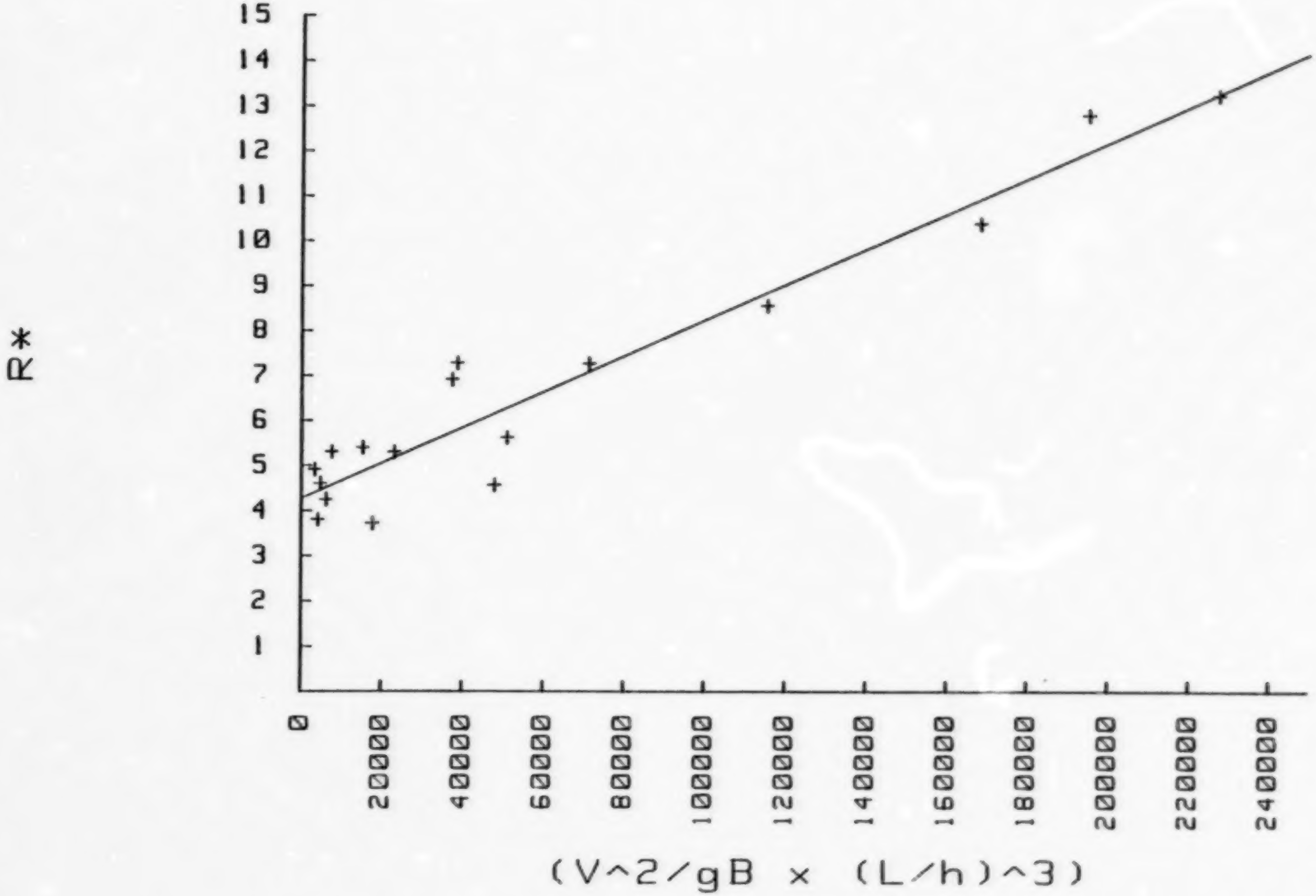
1252C TOWED RESISTANCE TESTS OF 140' WTGB



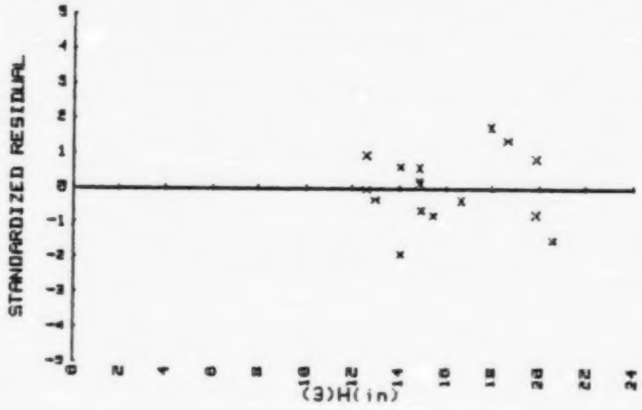
```
**************************************************************************
MULTIPLE LINEAR REGRESSION ON DATA SET:

                1252C TOWED RESISTANCE TESTS OF 140' WTGB
**************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable(s) = (19)SIG**
                                    (13)V*

                                                       STANDARD     COEFF. OF
VARIABLE      N          MEAN         VARIANCE         DEVIATION    VARIATION


SIG**        17      126.90959       948.66793         30.80045     24.26960
V*           17        1.04549          .35579           .59649     57.05321
R*           17        6.67658         8.77822          2.96281     44.37609


                       CORRELATION MATRIX


                     V*         R*
SIG**          .0736498   .2506746
V*                        .8710260


                         ANALYSIS OF VARIANCE TABLE


SOURCE          DF       SUM OF SQUARES          MEAN SQUARE       F-VALUE


TOTAL           16           140.45147
----------
```

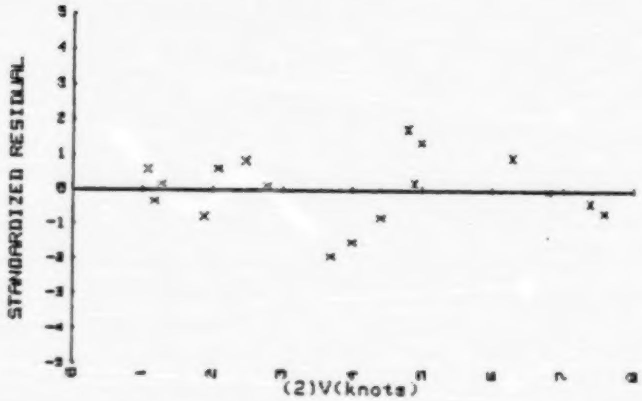
```
***************************************************************************
POLYNOMIAL REGRESSION ON DATA SET:

                 1252C TOWED RESISTANCE TESTS OF 140' WTGB
***************************************************************************

--where:  Dependent variable = (12)R*
          Independent variable = (23)VFINAL



                                                       STANDARD     COEFF. OF
VARIABLE      N          MEAN           VARIANCE       DEVIATION     VARIATION
VFINAL       17   61128.98081   5162460585.13935     71850.26503     117.53879
R*           17       6.67658            8.77822         2.96281      44.37609

CORRELATION =   .96103


SELECTED DEGREE OF REGRESSION =  1
R-SQUARED =  .92358
STANDARD ERROR OF ESTIMATE = .845888301041


                        ANALYSIS OF VARIANCE TABLE


SOURCE            DF       SUM OF SQUARES          MEAN SQUARE         F-VALUE

TOTAL             16            140.45147
REGRESSION         1            129.71856            129.71856          181.29
X^1                1            129.71856            129.71856          181.29
RESIDUAL          15             10.73291               .71553


                 REGRESSION COEFFICIENTS          STANDARD ERROR
VARIABLE         STD. FORMAT          E-FORMAT     REG. COEFFICIENT     T-VALUE

'CONSTANT'          4.25410  .425410276512E+01               .27287       15.59
 X^1                 .00004  .396289622919E-04              0.00000       13.46


                                   95 % CONFIDENCE INTERVAL
                 COEFFICIENT         LOWER LIMIT          UPPER LIMIT

'CONSTANT'           4.25410             3.67234              4.83586
 X^1                  .00004              .00003               .00005
```

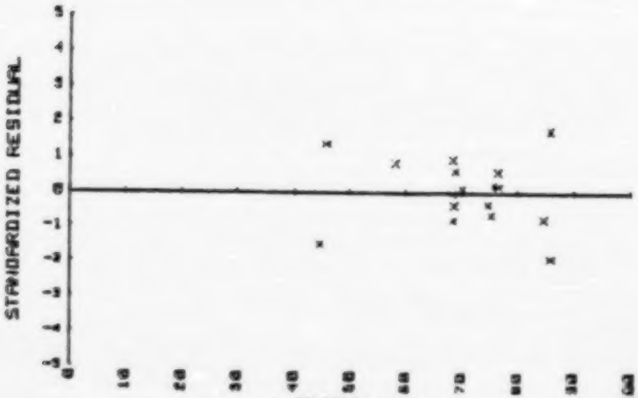
1252C TOWED RESISTANCE TESTS OF 140′ WTGB



```
                              TABLE OF RESIDUALS


                                                                STANDARDIZED
OBS#      OBSERVED Y       PREDICTED Y        RESIDUAL          RESIDUAL        SIGNIF.
   1         3.69338          4.96856         -1.27518          -1.50750
   2         6.88864          5.74646          1.14218           1.35027
   3         5.27279          4.56369           .70910            .83829
   4         3.77670          4.43292          -.65622           -.77577
   5         7.25477          5.79624          1.45854           1.72426
   6         4.54412          6.16046         -1.61633          -1.91081
   7         5.27523          5.17926           .09597            .11346
   8        12.78833         11.99919           .78913            .93291
   9        13.23067         13.27736          -.04669           -.05520
  10         4.88409          4.39689           .48720            .57596
  11         4.57051          4.45353           .11698            .13829
  12         7.24097          7.08739           .15358            .18156
  13         4.21372          4.50996          -.29623           -.35020
  14        10.37184         10.93463          -.56278           -.66532
  15         5.36844          4.86820           .50024            .59138
  16         8.52555          8.84366          -.31811           -.37607
  17         5.60212          6.28350          -.68138           -.80552

Durbin-Watson Statistic: 2.66114520907
```


1252C TOWED RESISTANCE TESTS OF 140' WTGB


1252C TOWED RESISTANCE TESTS OF 140' WTGB


1252C TOWED RESISTANCE TESTS OF 140' WTGB

APPENDIX F

TEST INSTRUMENTATION

APPENDIX F

TEST INSTRUMENTATION

1. Propeller Shaft Torque

The shaft was instrumented with strain gage bridges to measure torque.

Orientation and location of individual strain gages are illustrated on the adjoining page. Tensile strains due to torque lie on a helix 45° to the axis of the shaft. Compressive strains, of the same magnitude but opposite polarity, lie on the helix normal to the tensile strains. Referring to the figure, for torques as shown by the arrows, gages Q_1 and Q_3 are in tension while Q_2 amd Q_4 are in compression. The effect of thrust is cancelled because all four gages undergo identical strains and the bridge remains balanced. Bending effects are also cancelled because adjacent arm pairs of gages undergo identical strains. For proper cancellation of these unwanted strains, gages Q_1 and Q_2 were mounted as close together as possible, as were gages Q_3 and Q_4.

Two Micro-Measurement Type EA-06-250-TK-350 herringbone rosettes were installed on the shaft to form a 4-active-arm bridge. Strain sensed by an individual gage is expressed by:

$$\varepsilon = \frac{Q}{\pi G R^3} \tag{1-1}$$

where

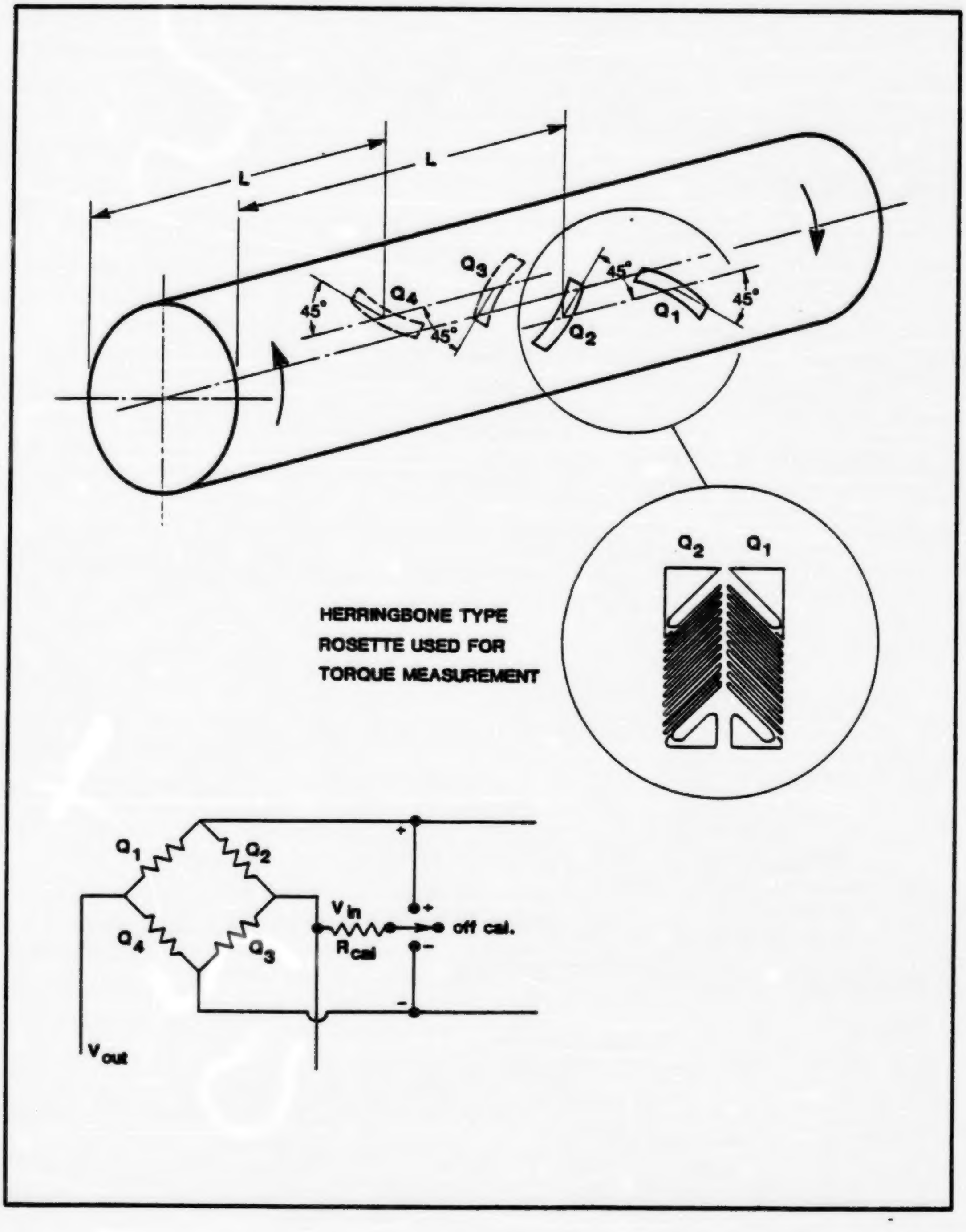
Q = torque (in/lbs)
ε = strain at 45° (in/in)
G = torsional rigidity (lbs/in^2)
R = outside radius (in)

Calibrations were performed by shunting one arm of the bridge with a precision calibration resistor. The relationship between the value of the resistor and simulated strain is given by:

$$R_{cal} = (1/N_{\varepsilon} F - 1)\ Rg \tag{1-2}$$

where

Rg = 350 Ω (gage resistance)
N = 4 (active bridge arms)
F = 2.0 (gage factor)
R_{cal} = shunt resistance in ohms
ε = strain at 45° (in/in)


L
L
45°
Q4
45°
Q3
45°
Q2
Q1
45°
Q2
Q1
Q1
Q2
Q4
Q3
+
+
V in
R cal
off cal.
-
-
V out

HERRINGBONE TYPE ROSETTE USED FOR TORQUE MEASUREMENT

TORQUE MEASUREMENT CONFIGURATION

2. Propeller Shaft Thrust

Strain gages to measure thrust were installed on the shaft at approximately the same locations as the torque gages. Orientation of the gages on each shaft is illustrated on the adjoining page.

Compressive strains due to thrust lie axially along the shaft. As the shaft is compressed along this axis, it expands slightly in diameter. This radial tensile strain is related to the axial compressive strain by Poisson's ratio, approximately 0.3 times the compressive strain. Referring to the figure, for the impressed thrust shown by the arrows, gages T_1 and T_2 are in compression with gages T_3 and T_4 in slight tension. Torque and bending are both cancelled in this configuration, for reasons analogous to those explained in Section 1. However, near perfect gage alignment is required when using this thrust measurement technique. Since thrust strains are normally much smaller than torque and bending strains, any misalignment in the gages will result in the thrust signal being influenced by the torque and bending strains to a large degree. For example, a misalignment of one degree in the thrust bridge gives an influence from the torque signal of 0.635 σ_T, or a resultant error of 63%. Thus, a one degree misalignment is relatively large.

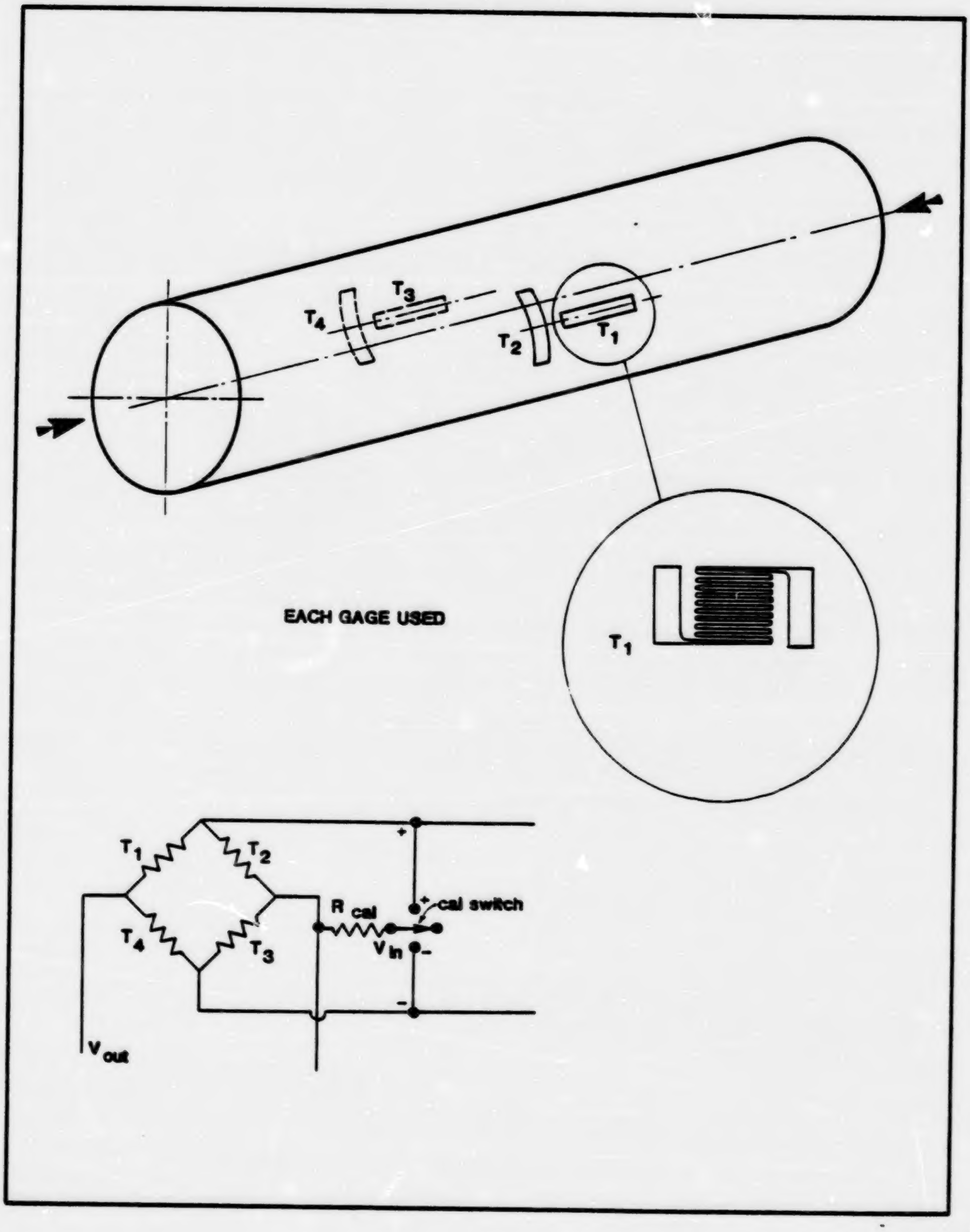
In order to reduce the possible extent of misalignments the shaft were fitted with weldable gages. These gages are mounted on metal shim stock which is then micro-welded to the shaft. The actual gage packages consisted of 2 gages in a 90° rosette on a single shim. The large shim makes handling, and therefore alignment, easier and more accurate.

Calibrations were performed shunting one arm of the bridge with a precision resistor as was done for torque. Simulated strain can be calculated from Equation 1-2 when 2.6 is substituted for N. The strain resulting from axial tension and compression due to thrust is given by:

$$\varepsilon = \frac{T}{A\,E} \qquad (2\text{-}1)$$

where

ε = axial strain (in/in)
E = elastic modulus of shaft (lbs/in^2)
A = cross-sectional area (in^2)
T = thrust (lbs)


T3
T4
T2
T1
EACH GAGE USED
T1
T1
T2
T4
T3
R cal
+
cal switch
V in
-
+
-
V out

THRUST MEASUREMENT STRAIN GAGE CONFIGURATION

3. Line Pull

The tension in the towing line was measured using a load sensing clevis pin manufactured by Strainsert. The pin is the same used for the POLAR SEA bollard and tow rope pull tests in 1981.

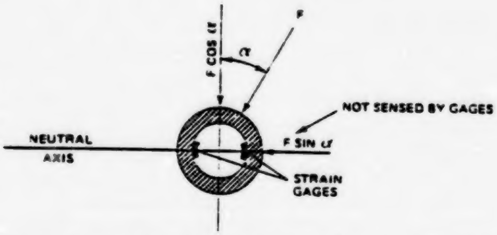
The pin, designed for use in a wire rope clevis socket, has a total load capacity of 180,000 lbs. Sensing is accomplished with internal strain gages, as described on the opposite page. Calibration was performed before the deployment by the manufacturer, and was checked regularly using stunt resistors.

DESCRIPTION

The Load Sensing Clevis Pin or Bolt is another unique strain gage transducer developed by Strainsert. It utilizes the internal strain gaging process perfected by Strainsert during the last 20 years and used so successfully in Strainsert Bolts, and Strainsert Flat Load Cells. The Clevis Pin Load Cell offers possibilities for force measurement that have not been heretofore feasible.

The strain gages are sealed inside a small axial hole and are located at two different depths corresponding to zones "C" of the pin. In order to sense only those strains which are induced by the shear forces at these two sections, the gages are positioned and oriented with great precision, at a neutral plane relative to one specific direction of pin loading. The four strain gages (two at each location) are electrically connected to form a full bridge, the signal from each gage being additive so that the bridge output is proportional to the sum of the loads transmitted by the two shear planes of the pin. The circuit includes temperature compensating, signal trim and balance resistors terminating in suitable connector socket, and potted with sealing compound inside the gage hole.

If the force F is applied to the pin at other than the specified direction, the bridge output will be due to the component of the force along the sensitive direction, i.e. F cos α



PIN CROSS-SECTION WITH FORCE F ANGULARLY MISALIGNED. THE BRIDGE OUTPUT IS PROPORTIONAL TO F cos α

PERFORMANCE & SPECIFICATIONS

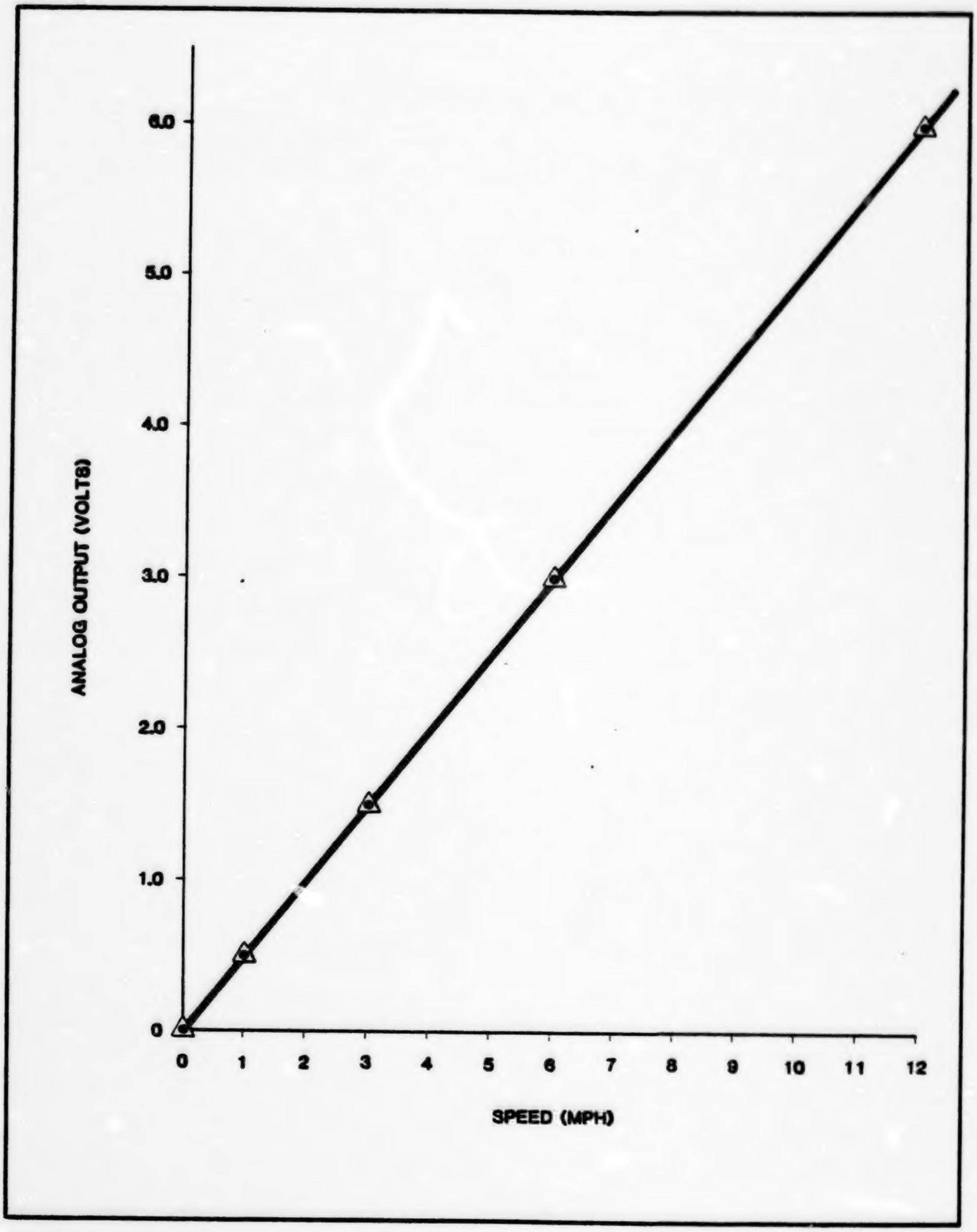
Bridge	350 Ω ± 3½ Ω		Span Calibration	± 0.25% FS
Excitation	12 V AC or DC		Temperature Effect	
Output Signal	1½ mV/V		on Zero	0.003% FS/°F
Non-Repeatability	± 0.15% FS	Nominal	on Output	0.008% load/°F
Non-Linearity	± 0.25% FS			(or better, as ordered)
Hysteresis	± 0.25% FS		Zero Balance	± 2% FS

STRAINSERT PIN DATA

4. Ship Speed

Ship speed, relative to the ice (or water) surface, was measured using a doppler shift radar modified for low speed operation. The unit will be mounted on the main deck and pointed slightly down and aft. This orientation insures that some surface roughness (broken ice pieces) is available to provide a steady return to the antenna.

The radar unit will consist of an antenna, which operates at 10.525 GH$_Z$, and a control/display unit. This display unit provides a digital readout in miles per hour and a triangular wave form voltage output proportional to speed. This voltage output is electrically integrated to provide a DC voltage proportional to speed. Calibrations were performed using low frequency tuning forks corresponding to 1.0, 3.0, 6.0, and 12.0 miles per hour, as shown on the adjoining page, and the cosine correction for antenna declination is performed in the software.



RADAR TUNING FORK CALIBRATIONS

5. Shaft RPM

Shaft RPM is available in the main control section of the engine space. In a manner similar to that used on the POLAR Class icebreakers, a buffer amplifier was used to isolate the instrumentation system from the ship's control circuitry.

The 60 volt output of the ship's tachometer/generators was altered with the buffer amplifier/attenuator to provide a suitable signal for the instrumentation amplifers. Calibration of the output was accomplished using a strobe system.